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Zhuang et al.

(54) ELECTRICALLY-CONTROLLED, VARIABLE FOCAL LENGTH LIQUID-BASED OPTICAL IMAGING APPARATUS AND METHOD

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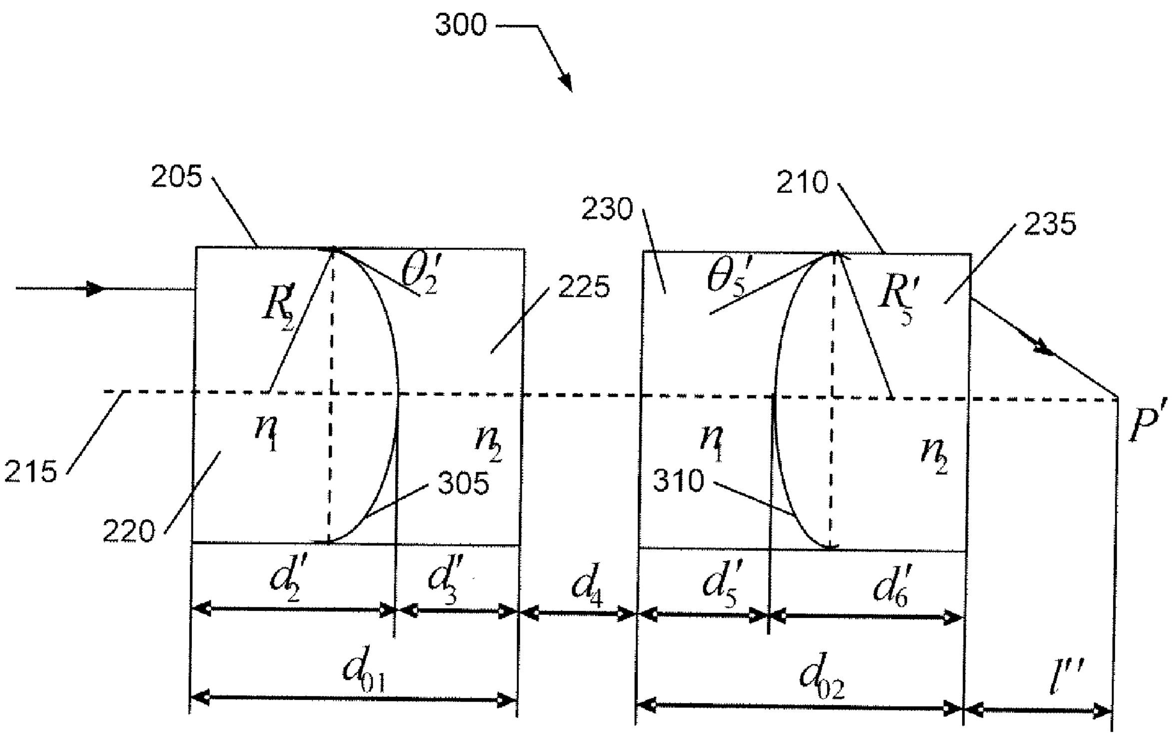
(57) **ABSTRACT**

An optical imaging apparatus having a variable focal length is disclosed. The optical imaging apparatus includes a first double-liquid variable focal lens and a second double-liquid variable focal lens. The first and second double-liquid variable focal lenses are aligned on a common axis and operable to have opposite varying curvatures.



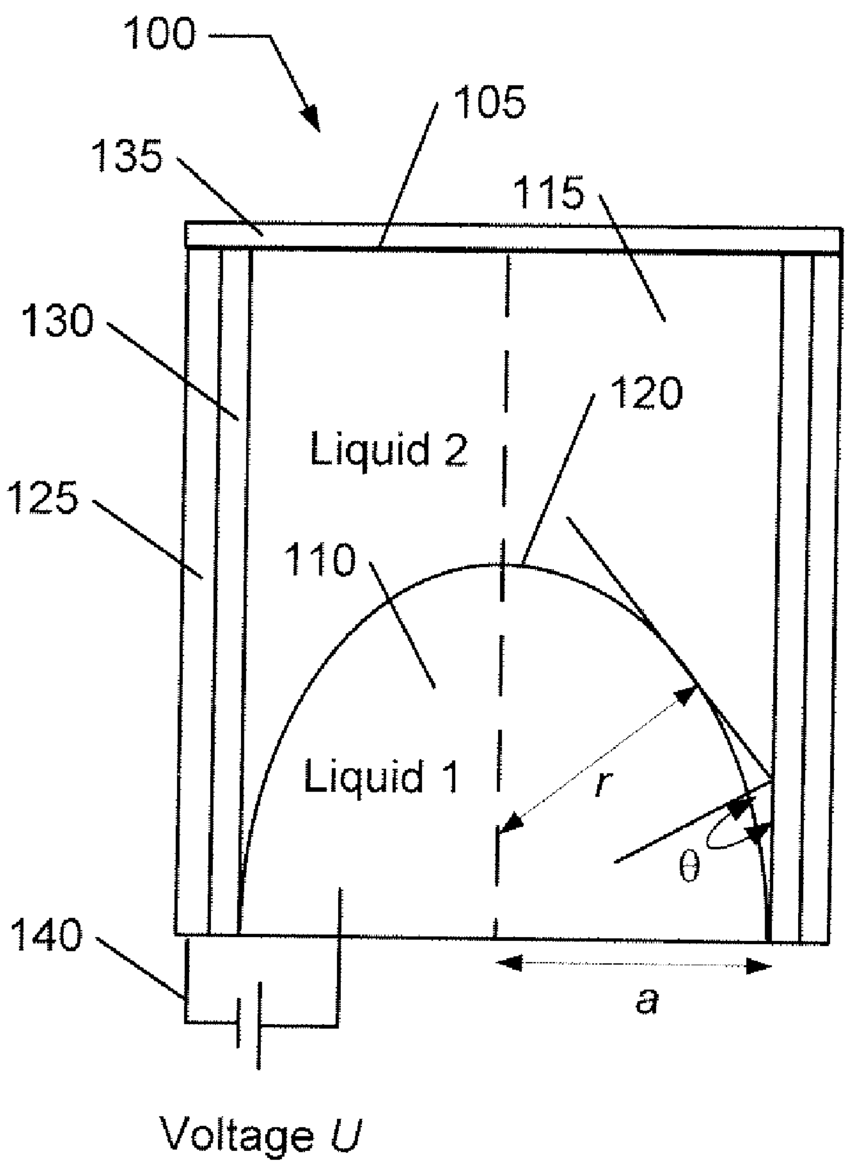


FIG. 1
(Prior Art)

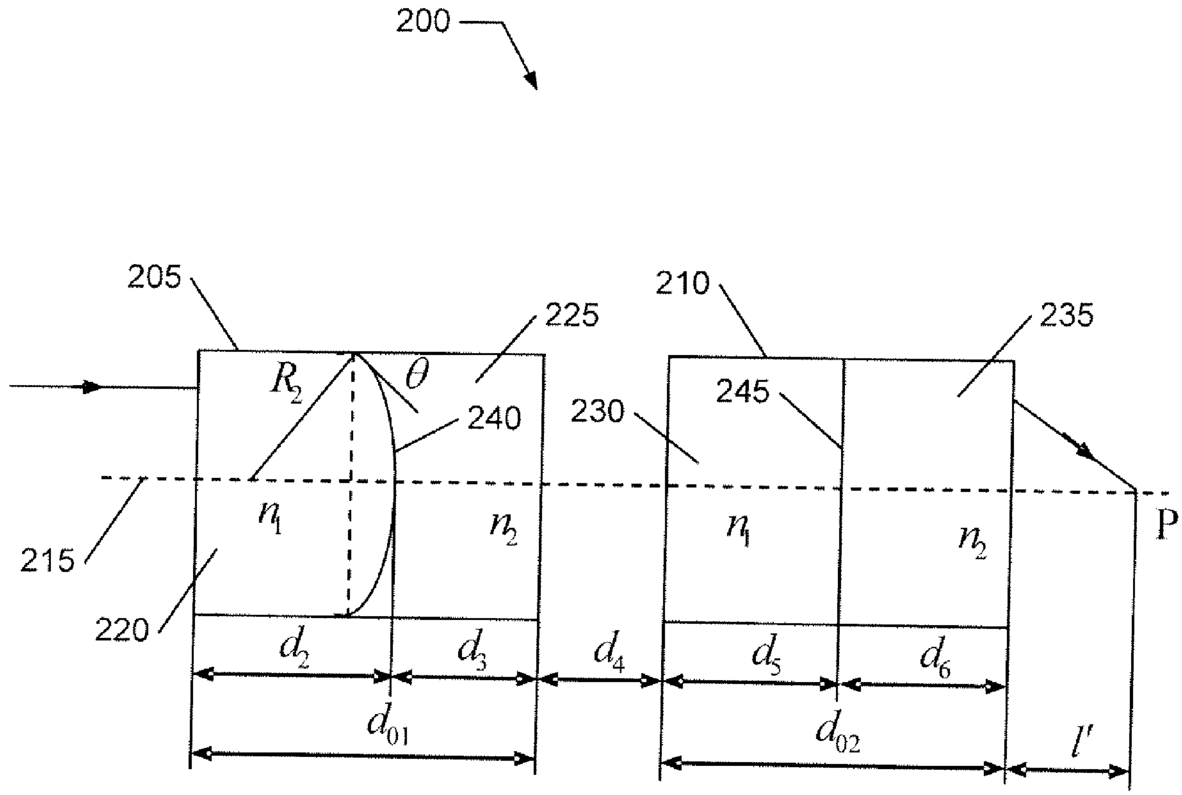

200
205
210
225
235
R_2
θ
240
230
245
215
220
n_1
n_2
n_1
n_2
P
d_2
d_3
d_4
d_5
d_6
d_{01}
d_{02}
l'

FIG. 2

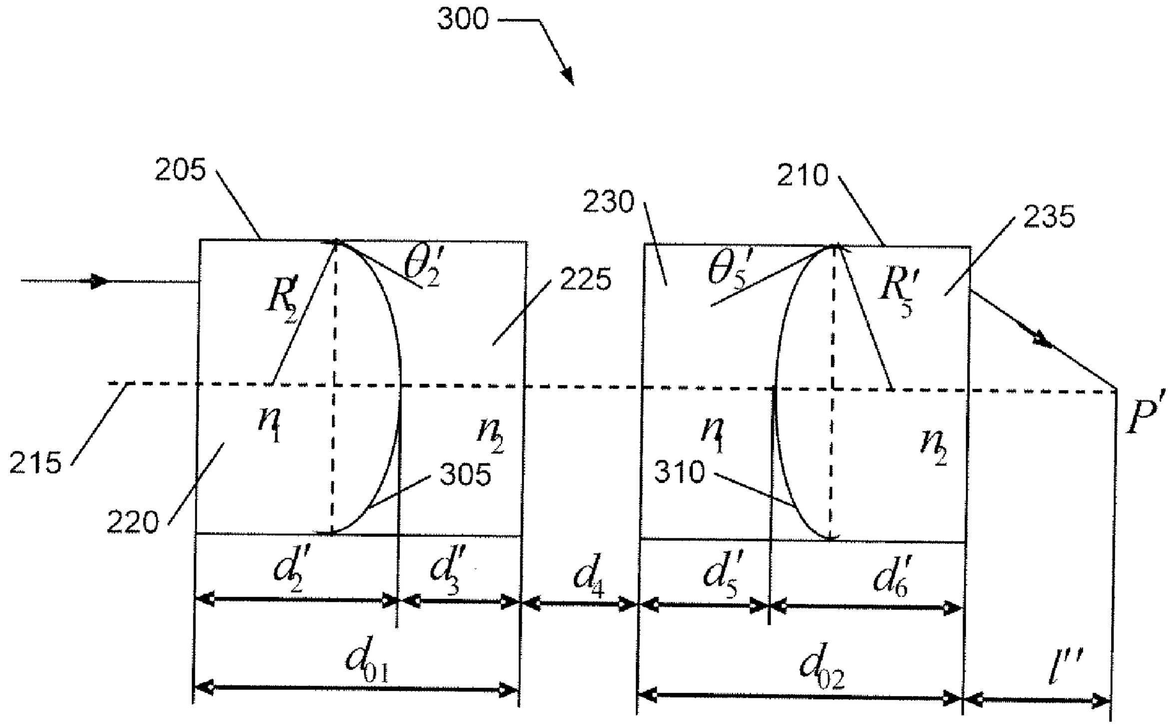

300
205
210
230
235
225
215
220
305
310
θ_2'
θ_5'
R_2'
R_5'
n_1
n_2
n_1
n_2
P'
d_2'
d_3'
d_4
d_5'
d_6'
d_{01}
d_{02}
l''

FIG. 3

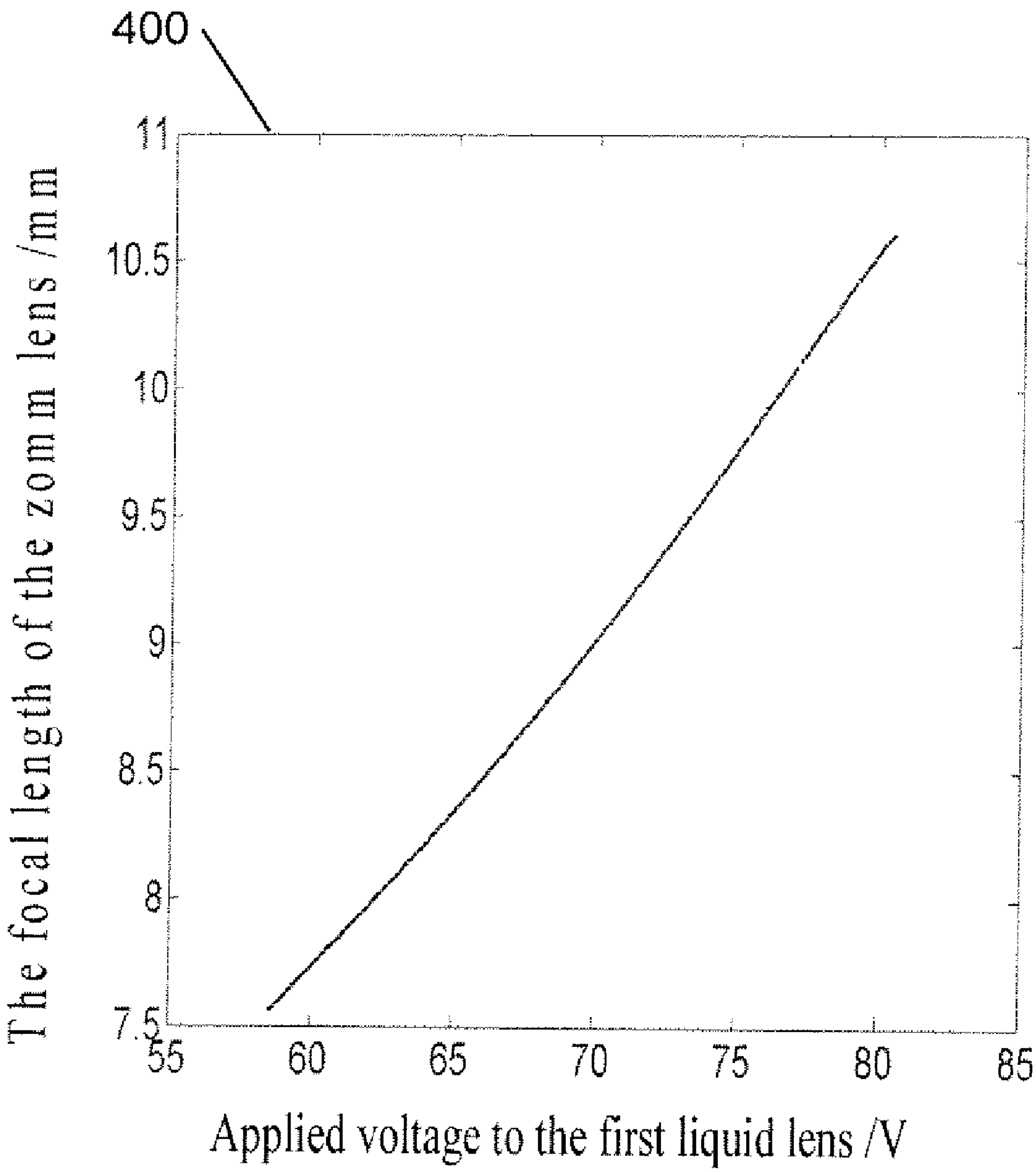

400
11
10.5
10
9.5
9
8.5
8
7.5
55
60
65
70
75
80
85
The focal length of the zomm lens /mm
Applied voltage to the first liquid lens /V

FIG. 4

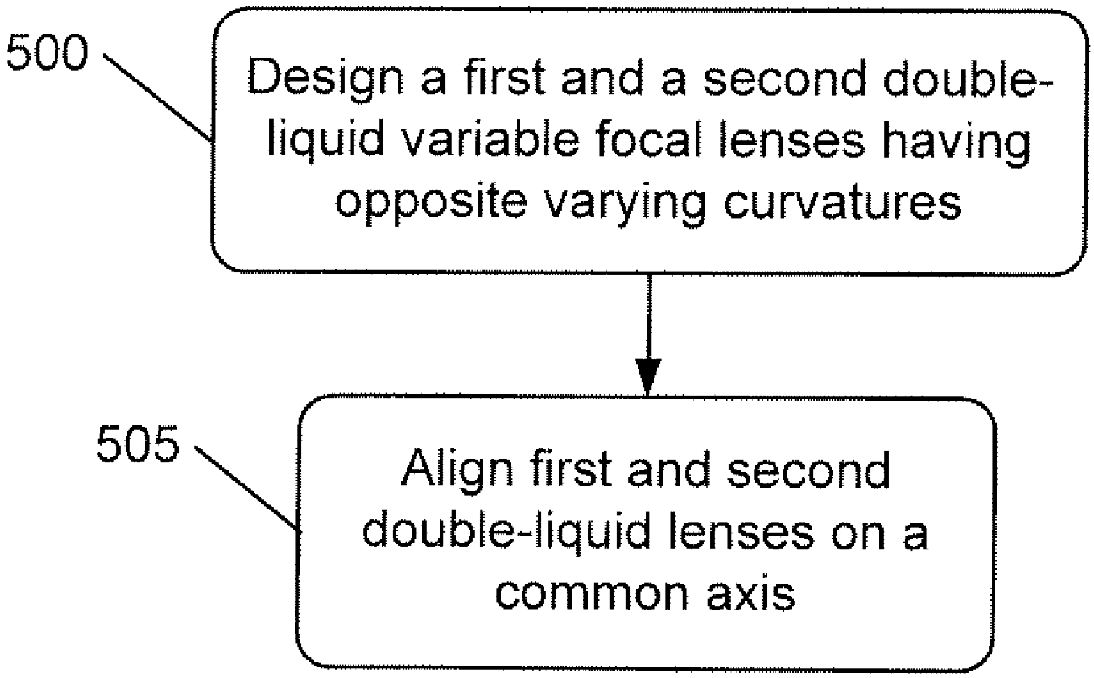

500
Design a first and a second double-liquid variable focal lenses having opposite varying curvatures
505
Align first and second double-liquid lenses on a common axis

FIG. 5

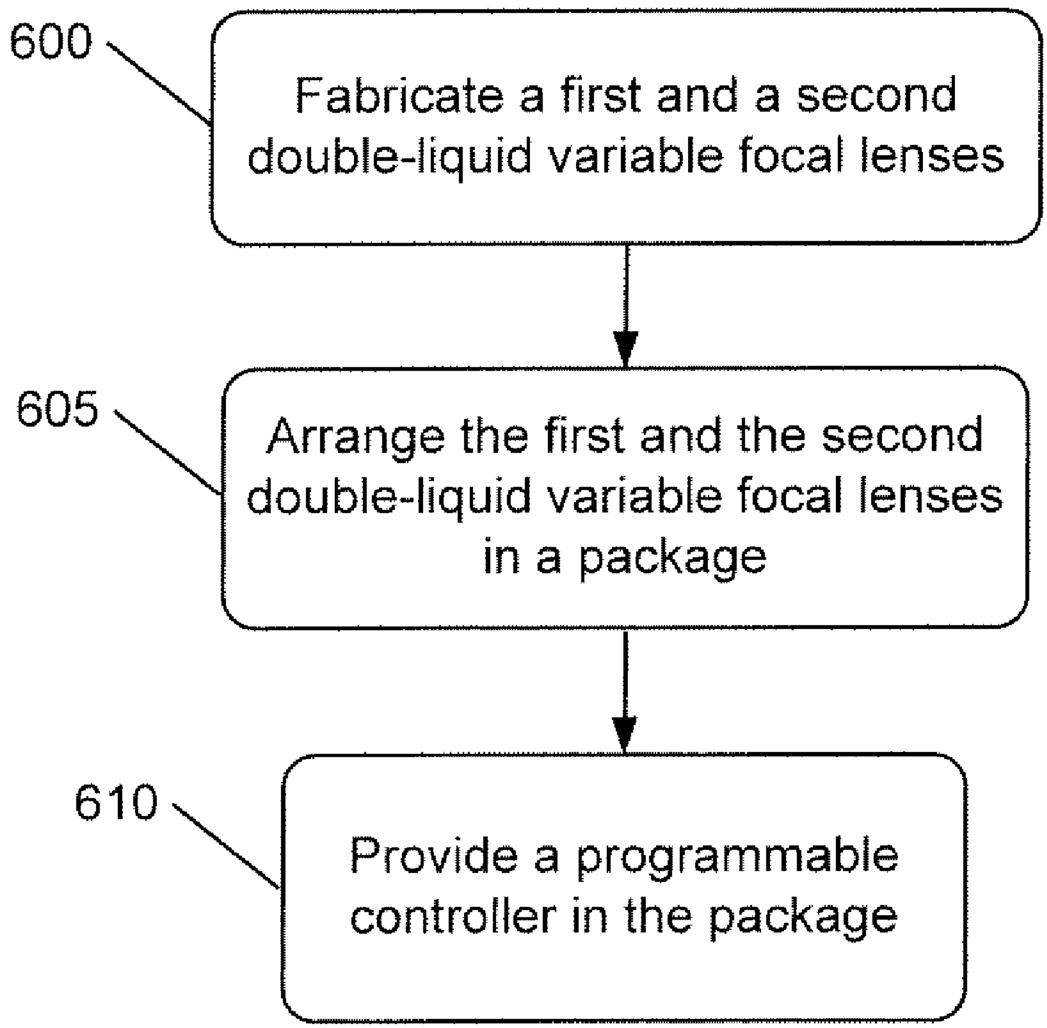

600
Fabricate a first and a second double-liquid variable focal lenses
605
Arrange the first and the second double-liquid variable focal lenses in a package
610
Provide a programmable controller in the package

FIG. 6

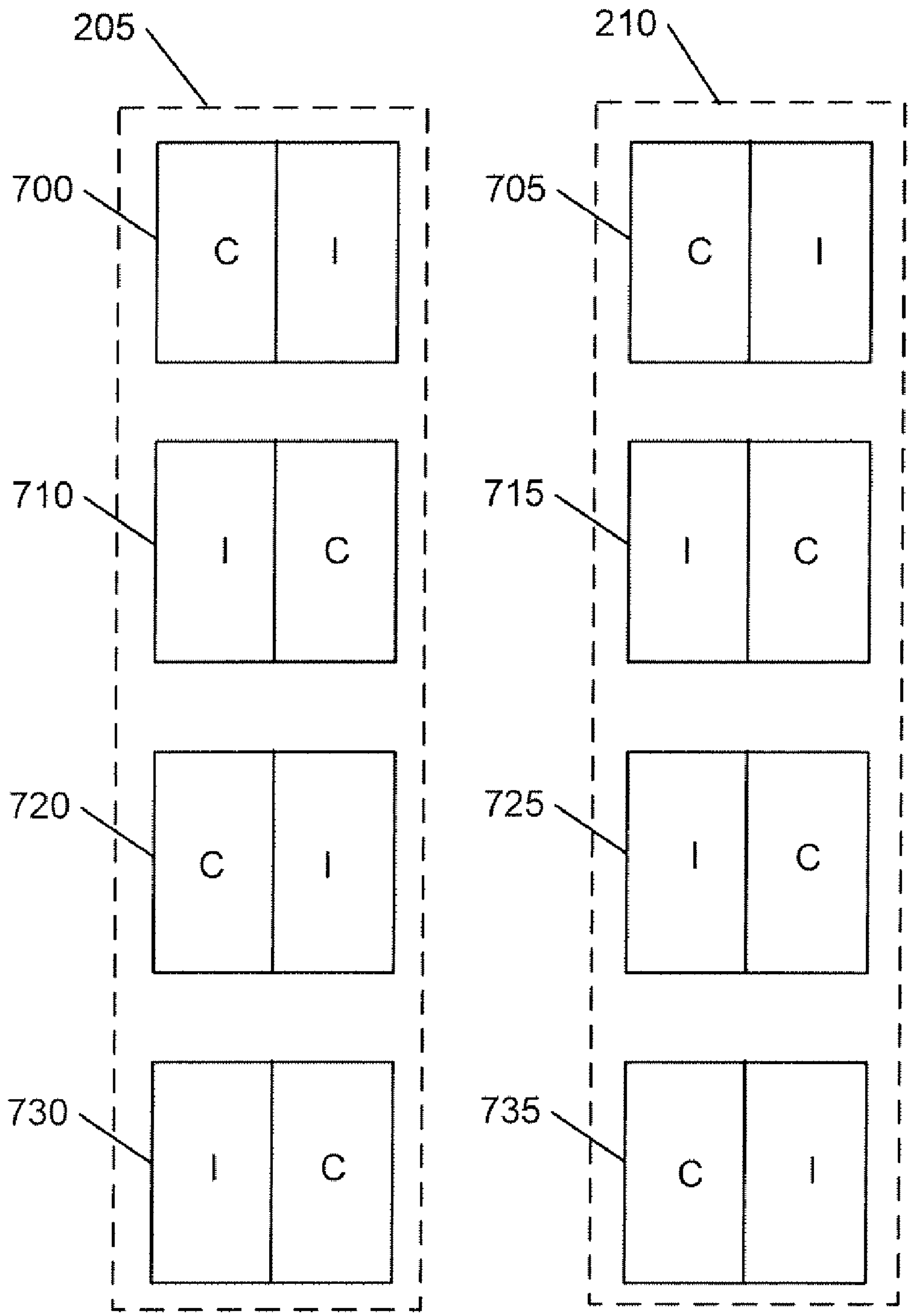


FIG. 7

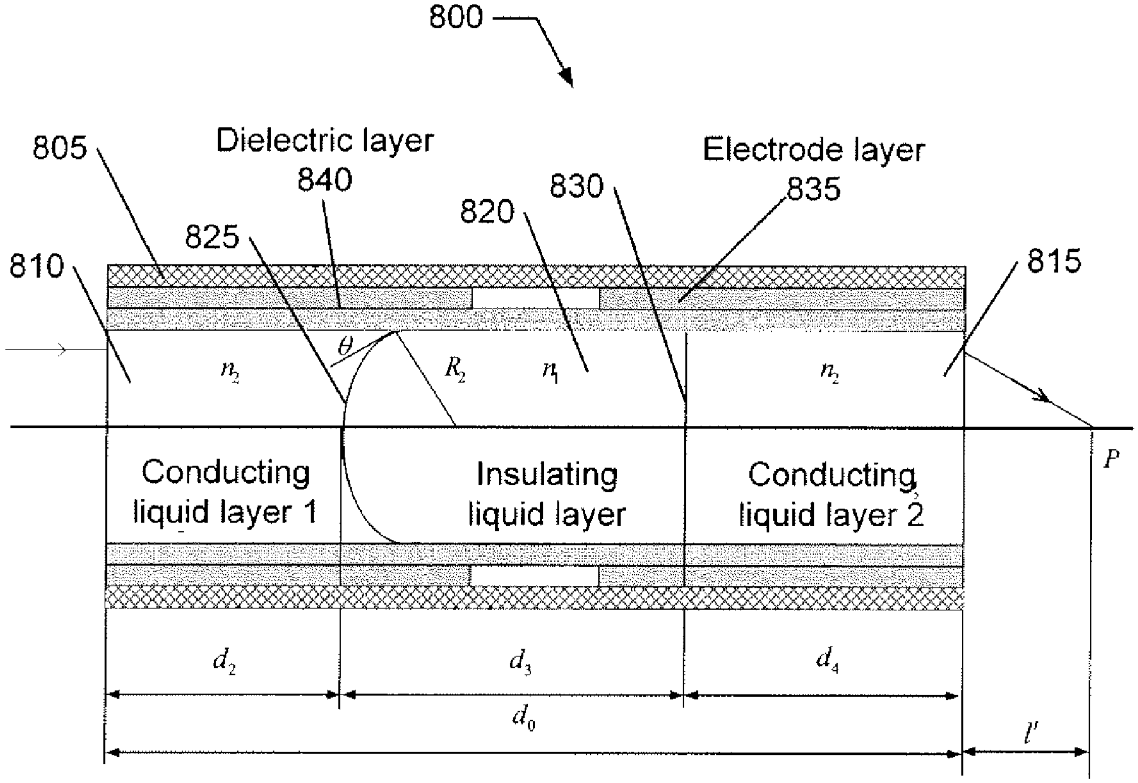

800
805
Dielectric layer
840
Electrode layer
835
830
820
825
810
815
θ
n_2
R_2
n_1
n_2
P
Conducting
liquid layer 1
Insulating
liquid layer
Conducting
liquid layer 2
d_2
d_3
d_4
d_0
l'

FIG. 8

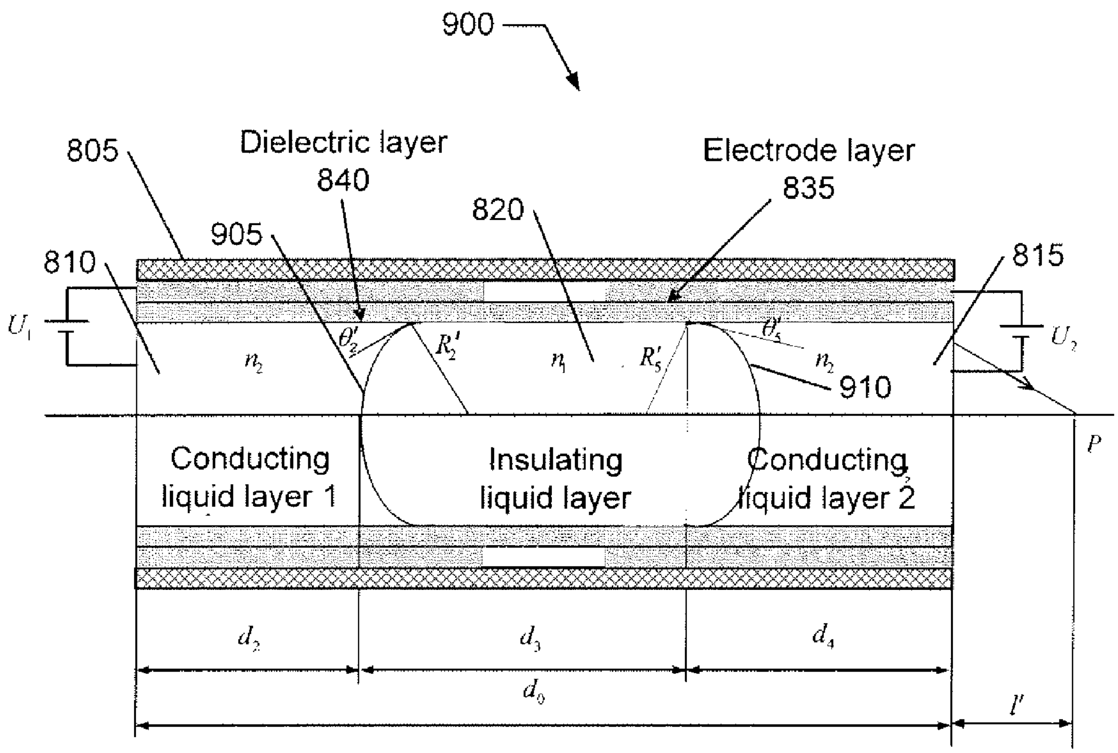

900
805
Dielectric layer
840
Electrode layer
835
820
905
810
815
U1
U2
n2
n1
n2
R'2
R'5
910
P
Conducting
liquid layer 1
Insulating
liquid layer
Conducting
liquid layer 2
d2
d3
d4
d0
l'

FIG. 9

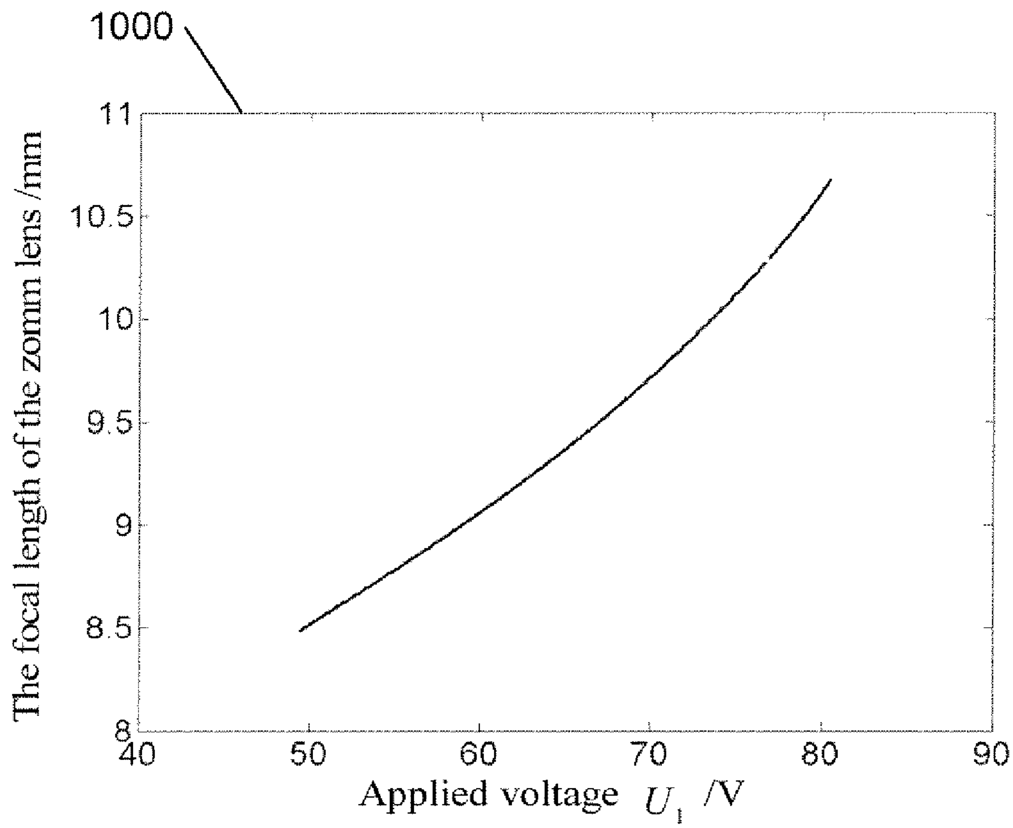

1000
The focal length of the zomm lens /mm
11
10.5
10
9.5
9
8.5
8
40
50
60
70
80
90
Applied voltage U_1 /V

FIG. 10

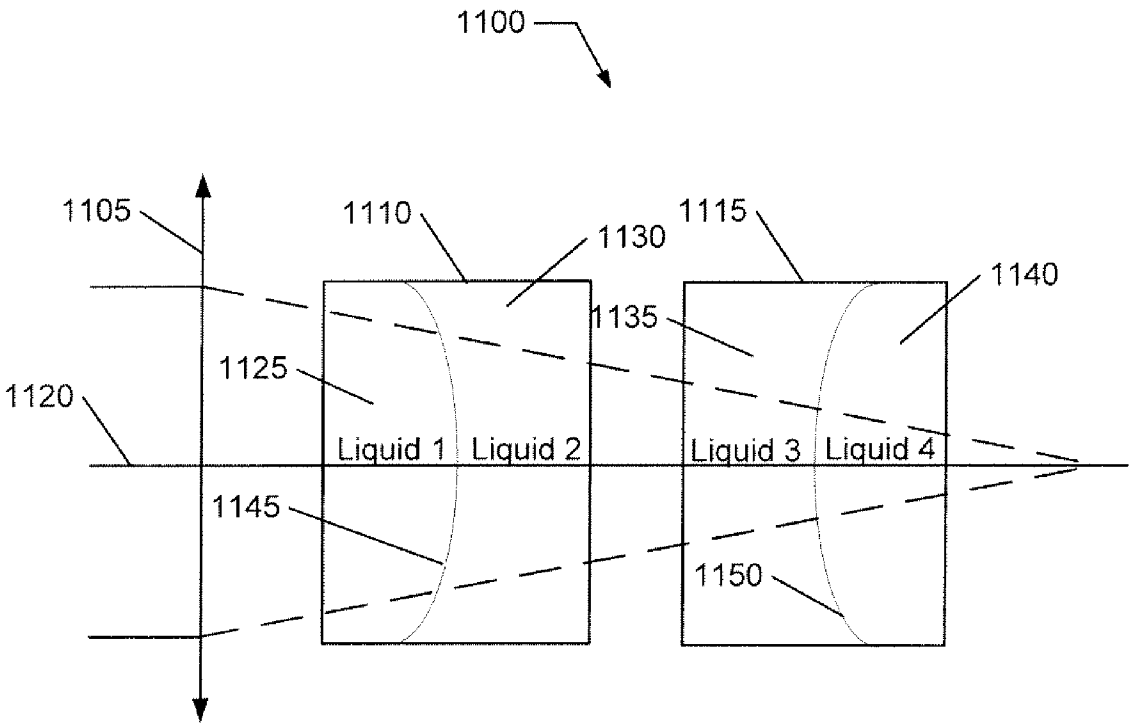

1100
1105
1110
1130
1115
1140
1135
1125
1120
Liquid 1
Liquid 2
Liquid 3
Liquid 4
1145
1150

FIG. 11

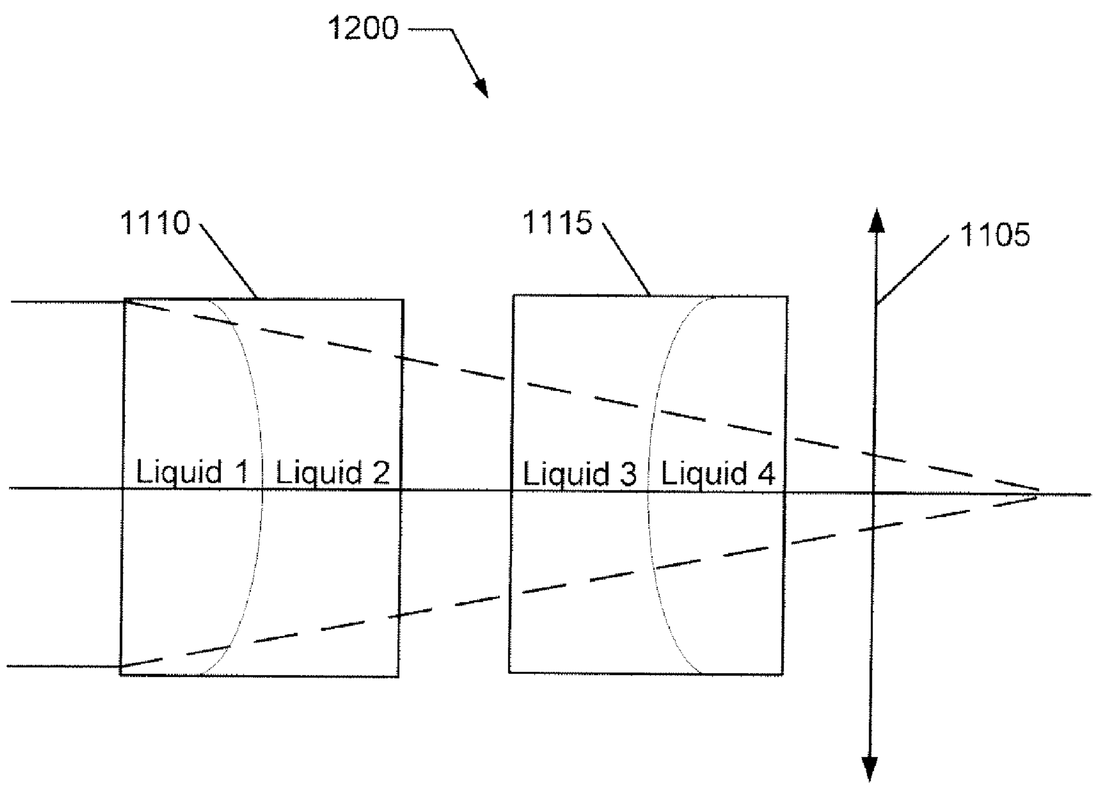


FIG. 12

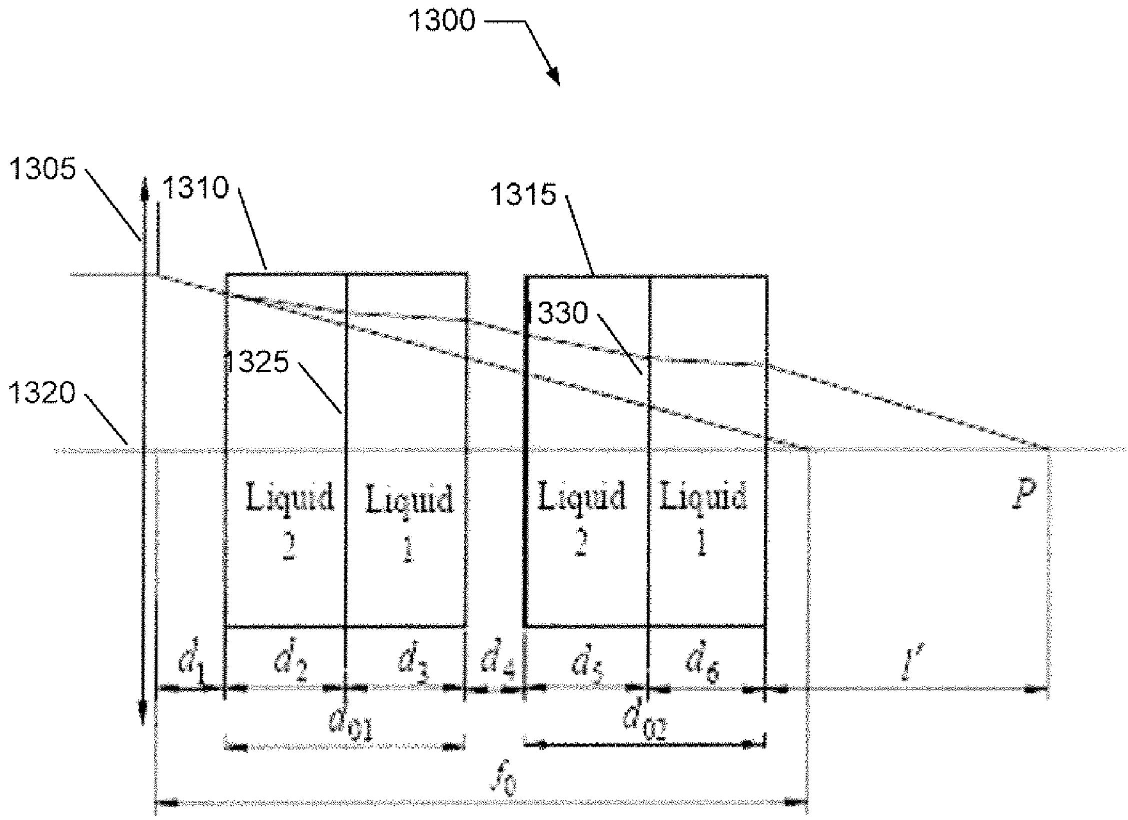

1300
1305
1310
1315
1330
1325
1320
Liquid 2
Liquid 1
Liquid 2
Liquid 1
P
d_1
d_2
d_3
d_4
d_5
d_6
l'
d_{01}
d_{02}
f_0

FIG. 13

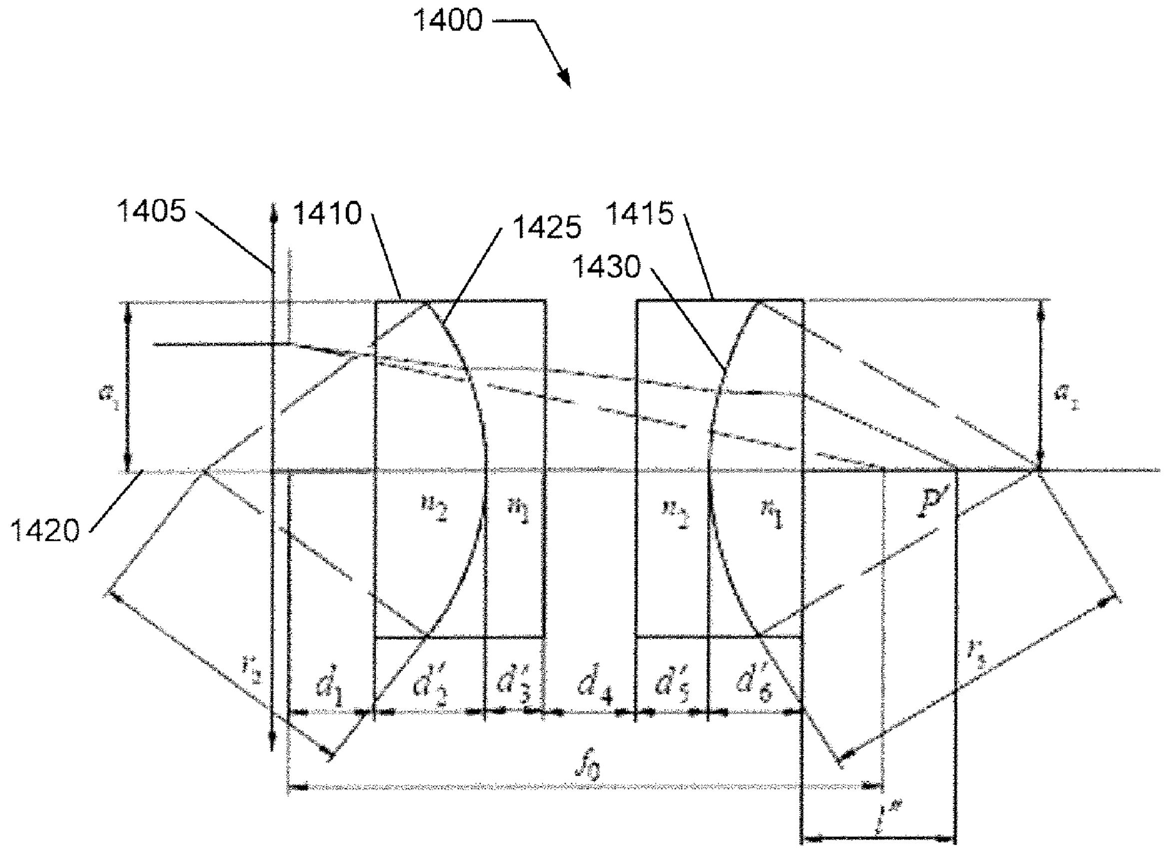


FIG. 14

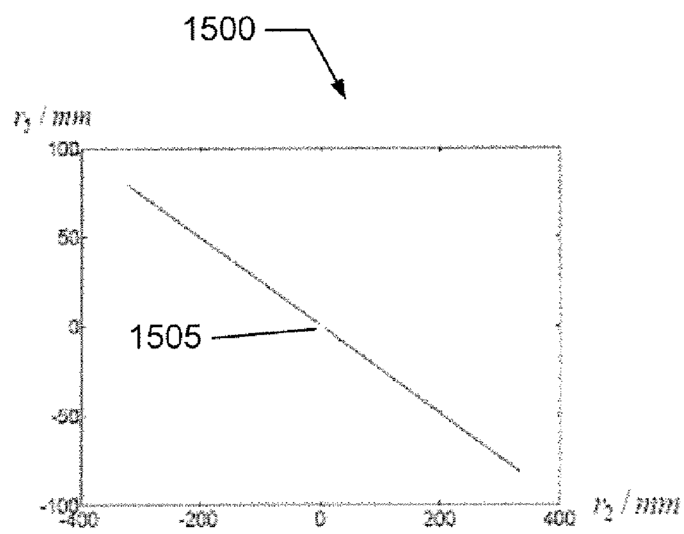


FIG. 15

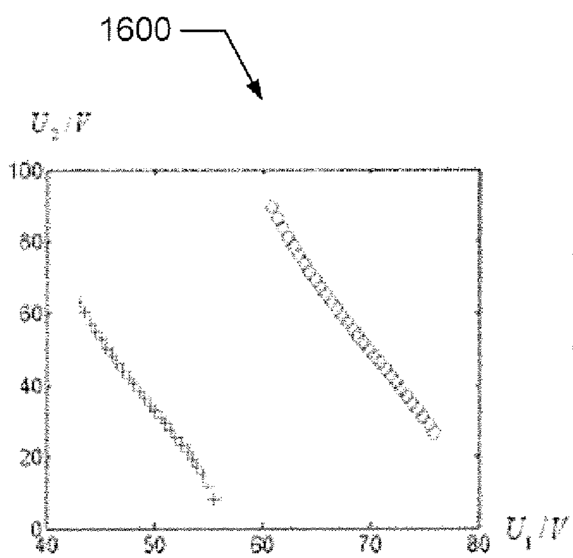


FIG. 16

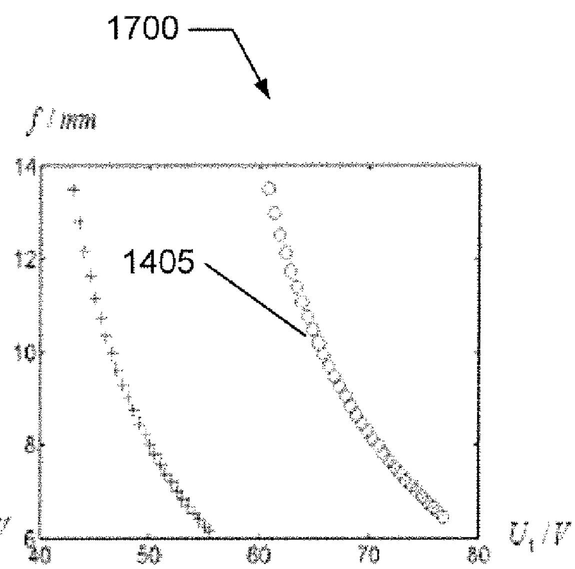


FIG. 17

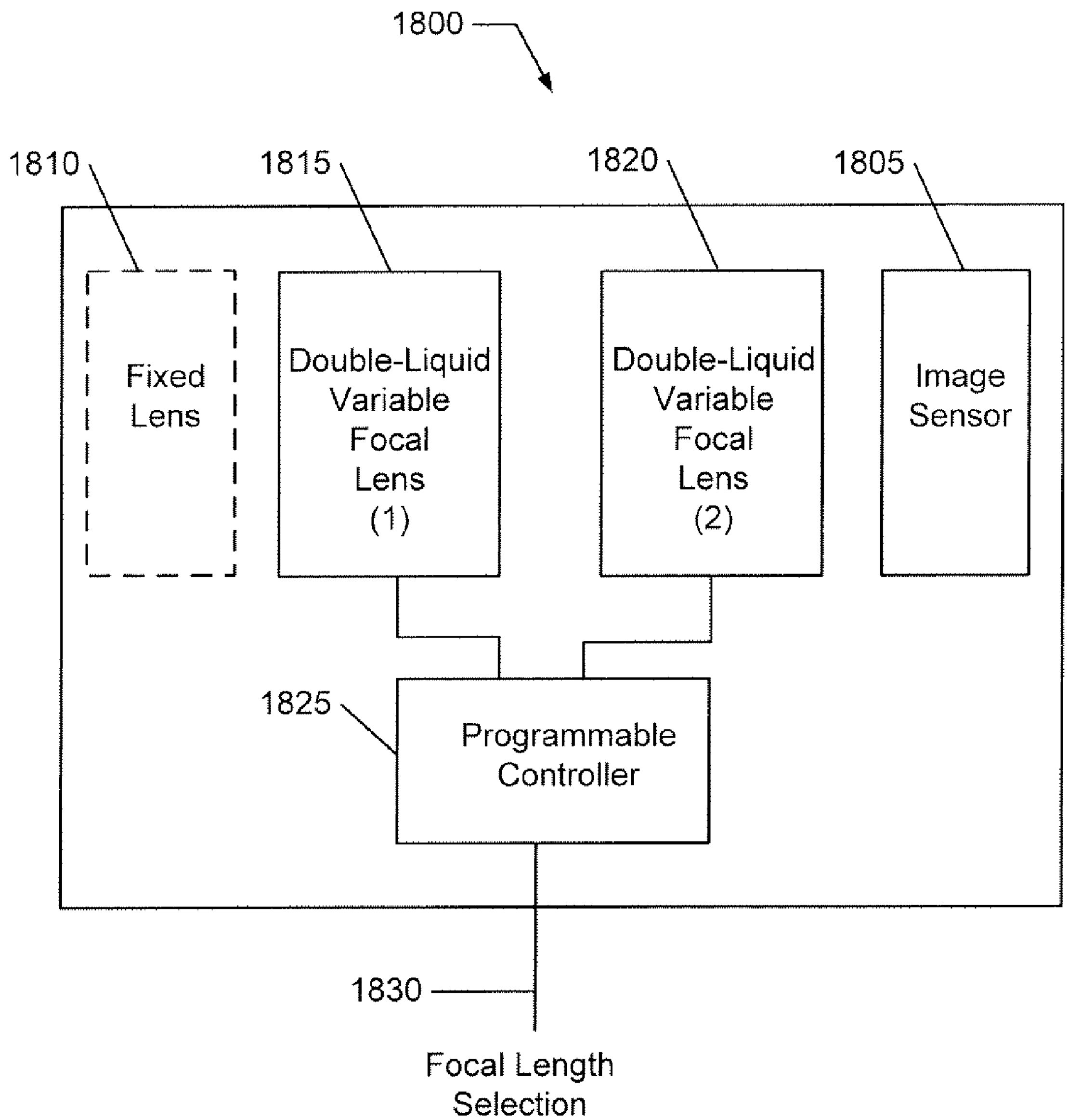

1800
1810
1815
1820
1805
Fixed Lens
Double-Liquid Variable Focal Lens (1)
Double-Liquid Variable Focal Lens (2)
Image Sensor
1825
Programmable Controller
1830
Focal Length Selection

FIG. 18

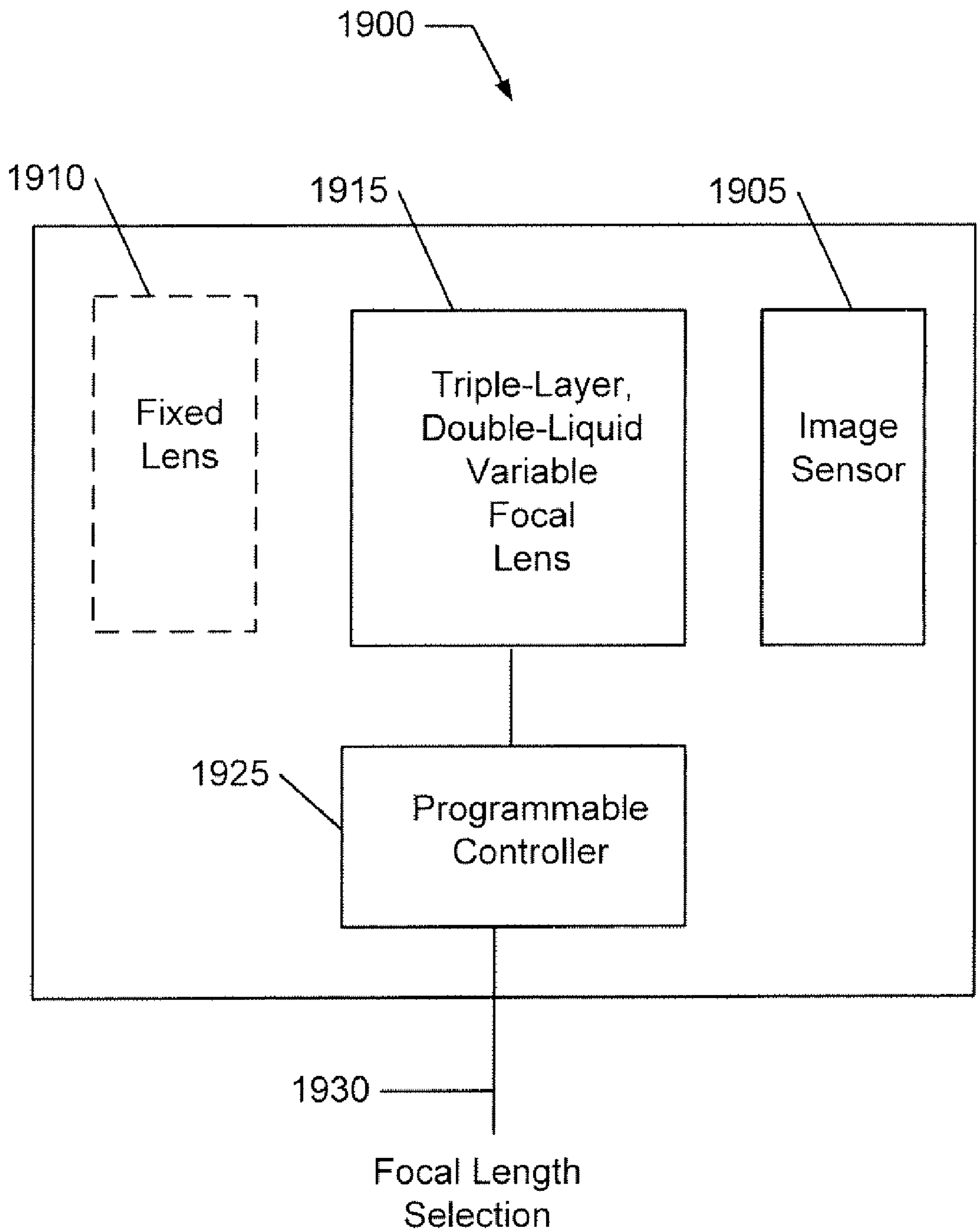

1900
1910
1915
1905
Fixed
Lens
Triple-Layer,
Double-Liquid
Variable
Focal
Lens
Image
Sensor
1925
Programmable
Controller
1930
Focal Length
Selection

FIG. 19

ELECTRICALLY-CONTROLLED, VARIABLE FOCAL LENGTH LIQUID-BASED OPTICAL IMAGING APPARATUS AND METHOD

FIELD OF THE INVENTION

[0001] This invention relates generally to liquid lenses. More particularly, this invention relates to an electrically-controlled, variable focal length optical imaging apparatus and method based on double-liquid lenses.

BACKGROUND OF THE INVENTION

[0002] Optical lenses are optical devices that refract light to form an image of an object. They are fundamental components of any imaging system, including viewing devices such as glasses, binoculars and telescopes, scientific instruments such as microscopes and spectroscopes, analog and digital cameras, video cameras, medical devices such as optical catheter and endoscopes, and the like. There are many types of optical lenses available today, manufactured from various materials and having different characteristics. Selecting a lens for use in an imaging device depends mostly on how the lens' characteristics enable the device to perform its specialized functions.

[0003] One of the most decisive characteristics is the lens' focal length. The focal length of an optical lens is a measure of how strongly it converges (i.e., focuses) or diverges (i.e., diffuses) light. Light rays from a distant object enter a lens and converge into a region called the focal point. The distance between the center of the lens and the focal point is the focal length. In cameras, for example, the lenses are separated from the film or image sensor by their focal length.

[0004] The focal length of a lens is determined by the curvature, thickness and type of materials used in the lens. Short focal lengths yield wider angles of view and higher magnification. A lens with a shorter focal length also has greater optical power than one with a long focal length. In a camera, this translates into the amount of scene that is captured in the film or sensor. Lenses with shorter focal length are able to capture more of an image scene than lenses with longer focal length. Smaller objects require shorter focal lengths and vice-versa.

[0005] The focal length of a lens may therefore need to be adjusted in many imaging devices in order to properly capture an image of an object. Lenses having fixed focal lengths may typically require a mechanical or other optical compensation assembly to move the lenses so images are captured with the appropriate magnification. In a camera, for example, the focal length of a zoom lens may be adjusted by moving a set of fixed lenses closer or farther away from the film or image sensor. As the set is moved, an image of an object can be lined up so it falls directly on the film or image sensor.

[0006] Both the mechanical and optical compensation techniques require precise control of the mechanical position of the lens. Additionally, precisely spaced cams or gears must be used to implement synchronized movements. Such conventional solutions have been considered to be complicated, fragile and thus expensive. The assembly together with the lens set may be heavy and slow to adjust. They are also not convenient to be implemented in small spaces, such as in miniature cameras used in mobile devices. In these cases, mechanical movement is less suited because it makes the devices susceptible to wear and is hampered by surface tension.

[0007] An alternative approach is to use lenses having variable focal lengths. Such lenses may have a variable surface or material. For example, a refraction-diffraction combined variable focal lens based on LCD Fresnel lenses has been previously proposed. Electrically motivated, the LCD Fresnel lenses can vary the focal length by changing the refractive index of the LCD material without involving any motorized movements. However, disadvantages such as large chromatic aberrations and difficulties in keeping the image plane fixed pose an obstacle to the practical use of these lenses.

[0008] Variable focal lenses based on the electrowetting principle have also been proposed. The electrowetting principle refers to the change in the surface interface between two materials as a result of a voltage difference. A conventional variable focal lens based on electrowetting is illustrated in FIG. **1**. Variable focal lens **100** is a double-liquid lens formed with a cylindrical chamber **105** enclosing two liquids, liquid **110** and liquid **115**. Liquid **110** is a conducting liquid with refractive index n_1 and liquid **115** is an insulating liquid with refractive index n_2. As a result, liquid interface **120** between the two liquids **110**-**115** acts as a spherical lens.

[0009] A thin electrode layer **125** and a hydrophobic dielectric layer **130** with thickness d and relative permittivity ϵ_r are coated inside the cylindrical chamber **105**, which is typically a glass chamber with a transparent cap **135** placed on top. A voltage U is applied with a power supply **140** between the conducting liquid **110** and the electrode layer **125**. The applied voltage results in a surface charge along the two sides of hydrophobic dielectric layer **130** between electrode layer **125** and conducting liquid **110**. Because the amount of liquid inside cylindrical chamber **105** remains the same, this additional force results in a change in radius of curvature of interface **120** between the two liquids **110**-**115**. The relationship between the applied voltage U and the changing radius r of the liquid interface **120** can be described as follows:

$$r=-a/[\cos\theta_0+\epsilon_0\epsilon_r U^2/(2\gamma_{12}d)] \quad (1)$$

where a is the inner radius of the cylindrical chamber **105**, θ_0 is the initial contact angle when there is no external voltage applied, ϵ_a is the permittivity of free space and γ_{12} is the tension coefficient of liquid interface **120** between liquids **110**-**115**.

[0010] Unlike conventional variable focal lenses, double-liquid variable focal lens **100** changes its focal length electrically rather than mechanically. The disadvantages of other conventional variable focal lenses, such as the LCD Fresnel lenses described above, are also avoided. Furthermore, because of the cylinder geometry of lens **100**, interface **120** stays well centered, even when changing its curvature. By matching the density of liquids **110**-**115**, lens **100** becomes stable against shocks and vibrations.

[0011] Additionally, the switching speed of lens **100** is very small for the typical applied voltages, e.g., under 20 ms for a 3 mm diameter lens, thereby making double-liquid variable focal lenses particularly suitable for use in small devices. However, one double-liquid variable focal lens cannot keep the image plane fixed while it changes its focal length. A fixed image plane ensures that the acquired image is properly focused and formed on the image acquisition surface, such as a film or image sensor.

[0012] Accordingly, it would be desirable to provide an optical imaging apparatus and method based on double-liquid lenses that are capable of achieving a variable focal length and an invariable image plane without any mechanical movements.

SUMMARY OF THE INVENTION

[0013] The invention includes an optical imaging apparatus having a variable focal length. The optical imaging apparatus includes a first double-liquid variable focal lens and a second double-liquid variable focal lens. The first and second double-liquid variable focal lenses are aligned on a common axis and operable to have opposite varying curvatures.

[0014] An embodiment of the invention includes a method for providing a plurality of focal lengths without requiring mechanical movement. A first double-liquid variable focal lens and a second double-liquid variable focal lens are designed and operable to have opposite varying curvatures. The first and second double-liquid variable focal lenses are aligned on a common axis.

[0015] Another embodiment of the invention includes a method of fabrication of an optical imaging apparatus having a variable focal length. A first and a second double-liquid variable focal lenses are fabricated. The first and the second double-liquid variable focal lenses are arranged in a package. A programmable controller is provided in the package to apply a first voltage to the first double-liquid variable focal lens and a second voltage to the second double-liquid variable focal lens. The first voltage controls a first curvature on the first double-liquid variable focal lens and the second voltage controls a second curvature on the second double-liquid variable focal lens.

[0016] A further embodiment of the invention includes a programmable multi-focal camera. The programmable multi-focal camera has an image sensor to generate image data from an optical image and a programmable optical assembly to capture the optical image. The programmable optical assembly has a first and a second double-liquid variable focal lens and a programmable controller configured to independently address a first voltage to the first double-liquid variable focal lens and a second voltage to the second double-liquid variable focal lens to provide a plurality of focal lengths and an invariable image plane at the image sensor.

[0017] Another embodiment of the invention includes a variable focal lens having a cylindrical chamber. A first and a second liquid layer holding a liquid of a first type are enclosed within the cylindrical chamber. A third liquid layer holding a liquid of a second type is placed in between the first and the second conducting liquid layers.

[0018] A further embodiment of the invention includes a method of fabrication of an optical imaging apparatus having a variable focal length. A triple-layer, double-liquid variable focal lens is fabricated, having a first and a second liquid layers holding a liquid of a first type and a third liquid layer holding a liquid of a second type placed in between the first and the second liquid layers. The triple-layer, double-liquid variable focal lens is arranged in a package. A programmable controller is provided in the package to apply voltages to the liquid layers.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The invention is more fully appreciated in connection with the following detailed description taken in conjunction with the accompanying drawings, in which like reference characters refer to like parts throughout and in which:

[0020] FIG. **1** illustrates a prior art double-liquid variable focal lens;

[0021] FIG. **2** illustrates an optical imaging apparatus constructed in accordance with an embodiment of the invention;

[0022] FIG. **3** illustrates an optical imaging apparatus in which two double-liquid variable focal lenses are operable to have opposite varying curvatures and constructed in accordance with an embodiment of the invention;

[0023] FIG. **4** illustrates a graph showing the focal length of an optical imaging apparatus constructed in accordance with an embodiment of the invention as a function of the voltage applied to the first double-liquid variable focal lens;

[0024] FIG. **5** illustrates a flow chart for providing a plurality of focal lengths without mechanical movements in accordance with an embodiment of the invention;

[0025] FIG. **6** illustrates a flow chart for fabricating an optical imaging apparatus having a variable focal length in accordance with an embodiment of the invention;

[0026] FIG. **7** illustrates multiple configurations for the double-liquid variable focal lenses used in the optical imaging apparatuses of FIGS. **2-3** in accordance with an embodiment of the invention;

[0027] FIG. **8** illustrates an optical imaging apparatus having a single, triple-layer, double-liquid variable focal lens constructed in accordance with an embodiment of the invention;

[0028] FIG. **9** illustrates an optical imaging apparatus having a single, triple-layer, double-liquid variable focal lens constructed in accordance with an embodiment of the invention;

[0029] FIG. **10** illustrates a graph showing the focal length of an optical imaging apparatus constructed in accordance with FIG. **9** as a function of the voltage applied to the triple-layer, double-liquid variable focal lens;

[0030] FIG. **11** illustrates an optical imaging apparatus constructed in accordance with an embodiment of the invention;

[0031] FIG. **12** illustrates an optical imaging apparatus constructed in accordance with another embodiment of the invention;

[0032] FIG. **13** illustrates a schematic diagram of an optical imaging apparatus when both double-liquid variable focal lenses operate with planar liquid interfaces in accordance with an embodiment of the invention;

[0033] FIG. **14** illustrates a schematic diagram of an optical imaging apparatus when both double-liquid variable focal lenses operate with non-planar liquid interfaces in accordance with an embodiment of the invention;

[0034] FIG. **15** illustrates a graph showing the interface radius of the second double-liquid variable focal lens as a function of the interface radius of the first double-liquid variable focal lens in accordance with an embodiment of the invention;

[0035] FIG. **16** illustrates a graph showing the voltage applied to the second double-liquid variable focal lens as a function of the voltage applied to the first double-liquid variable focal lens in accordance with an embodiment of the invention;

[0036] FIG. **17** illustrates a graph showing the focal length of an optical imaging apparatus constructed in accordance with an embodiment of the invention as a function of the voltage applied to the first double-liquid variable focal lens,

[0037] FIG. **18** illustrates a programmable multi-focal camera constructed in accordance with an embodiment of the invention; and

[0038] FIG. **19** illustrates a programmable multi-focal camera constructed in accordance with another embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0039] An optical imaging apparatus having a variable focal length is provided. The optical imaging apparatus is based on a double-liquid variable focal lens. As generally used herein, a double-liquid variable focal lens may be any lens formed of two liquids inside a chamber, such as, for example, the double-liquid variable focal lens shown in FIG. **1**. According to an embodiment of the invention, one liquid is a conducting liquid with refractive index n_1 and another liquid is an insulating liquid with refractive index n_2. The conducting and insulating liquids have substantially the same density, thereby resulting in a liquid interface between them that acts as a spherical lens.

[0040] In one embodiment, two double-liquid variable focal lenses are aligned on a common axis and operable to have opposite varying curvatures. The two lenses may be placed in a number of configurations described below depending on the position of the conducting and insulating liquids of the two lenses relative to each other. It is appreciated that opposite varying curvatures, as generally used herein, refer to curvatures that vary in opposite directions from each other to have opposite signs, for example, one curvature varying in a convex (positive) direction and another curvature varying in a concave (negative) direction. Opposite curvatures may have the same or a different radius.

[0041] In another embodiment, a triple-layer, double-liquid variable focal lens having three liquid layers is provided. This lens may be formed of a liquid layer holding a liquid of a first type placed in between two liquid layers holding a liquid of a second type. The liquid of the first type may be a conducting liquid and the liquid of the second type may be an insulating liquid. Conversely, the liquid of the first type may be an insulating liquid and the liquid of the second type may be a conducting liquid. The three liquid layers form two liquid interfaces that are operable to have opposite varying curvatures.

[0042] In a further embodiment, an optional fixed lens is aligned with two double-liquid variable focal lenses or with a single, triple-layer double-liquid variable focal lens. A fixed lens, as generally used herein, may be any lens having a fixed position in an optical device.

[0043] FIG. **2** illustrates an optical imaging apparatus constructed in accordance with an embodiment of the invention. Optical imaging apparatus **200** includes double-liquid variable focal lens **205** and double-liquid variable focal lens **210** aligned on common axis **215**. Double-liquid variable focal lenses **205-210** may be any double-liquid variable focal lens known to one of ordinary skill in the art, such as, for example, double-liquid variable focal lens **100** shown in FIG. **1**.

[0044] Double-liquid variable focal lenses **205-210** are formed of two liquids enclosed in a cylindrical chamber, such as liquids **220-225** in lens **205** and liquids **230-235** in lens **210**. Each one of liquids **220-225** and liquids **230-235** is a conducting liquid having a given refractive index, while the other one of liquids **220-225** and liquids **230-235** is an insulating liquid. For example, liquids **225** and **235** may be conducting liquids while liquids **220** and **230** may be insulating liquids. As described in more detail herein below, several configurations of conducting and insulating liquids may be used in lenses **205-210**.

[0045] In one embodiment, the same conducting liquid may be used in lenses **205-210**. Similarly, the same insulating liquid may be used in lenses **205-210**. The conducting liquid and the insulating liquids may have substantially the same density but different refractive indices, thereby resulting in a liquid interface between them that acts as a spherical lens, such as liquid interface **240** in lens **205** and liquid interface **245** in lens **210**.

[0046] As described above, a voltage may be applied between an electrode layer (not shown) coated inside the cylindrical chamber of lens **205** and the conducting liquid in each one of lenses **205-210** to alter the curvature of liquid interfaces **240** and **245** and change the focal length of lenses **205-210**, respectively. For example, liquid interface **240** in double-liquid variable focal lens **205** is altered in a positive direction to have a positive curvature while liquid interface **245** in double-liquid variable focal lens **210** has a planar curvature.

[0047] The effect of the applicable voltages on the curvature of the lenses can be described as follows. Let n_1 be the refractive index of the insulating liquids and n_2 be the refractive index of the conducting liquids, with $n_1>n_2$. Various optical distances between double-liquid variable focal lenses **205-210** are as illustrated, with l' representing the position of image point P from infinity, that is, the distance from the image point P to double-liquid variable focal lens **210**. As appreciated by one of ordinary skill in the art, image point P marks the location of the image plane. This distance can be expressed as follows:

$$l' = \frac{n_0}{n_2}\left(\frac{n_2}{n_1}\left(\frac{n_1}{n_0}\left(\frac{n_0}{n_2}\left(\frac{n_2 R_2}{n_2 - n_1} - d_3\right) - d_4\right) - d_5\right) - d_6\right) \tag{2}$$

where n_0 refers to the refractive index of air, R_2 refers to the radius of the curvature in double-liquid variable focal lens **205**. As described above, the radius R_2 is determined by the voltage applied to lens **205**, referred to as U_1. Voltage U_1 is related to the contact angle Θ and the radius a_1 of the cylindrical chamber in lens **205**, as follows:

$$R_2 = -\frac{a_1}{\cos\theta} \tag{3}$$

[0048] That is, the focal length of optical imaging apparatus **200** depends mainly on the value of U_1 in this case. The voltage applied to double-liquid variable focal lens **210**, referred to as U_2, does not affect the focal length of optical imaging apparatus **200**. This is because voltage U_2 results in a planar curvature for liquid interface **245** in double-liquid variable focal lens **210**. Changing the value of U_2 may result in a positive or negative curvature for liquid interface **245**. As described below, an invariable image plane requires double-liquid variable focal lenses **205-210** to have opposite varying curvatures.

[0049] Referring now to FIG. **3**, an optical imaging apparatus in which two double-liquid variable focal lenses are operable to have opposite varying curvatures and constructed in accordance with an embodiment of the invention is described. Optical imaging apparatus **300** includes double-liquid variable focal lens **205** and double-liquid variable focal lens **210** aligned on common axis **215**. Double-liquid variable focal lenses **205** has a liquid interface **305** with a positive curvature resulting from a voltage U_1 applied between an electrode layer (not shown) coated inside the cylindrical chamber of lens **205** and conducting liquid **225**. Similarly, double-liquid variable focal lens **210** has a liquid interface **310** with a negative curvature resulting from a voltage U_2

applied between an electrode layer (not shown) coated inside the cylindrical chamber of lens **210** and conducting liquid **235**.

[0050] The opposite varying curvatures of lenses **205-210** ensure that the image plane remains invariable while the focal length of optical imaging apparatus **300** changes. This is so because when the voltage U_1 becomes larger, the power of lens **205** also becomes larger (resulting in a positive curvature for lens **205**). To make the image plane invariable, the voltage U_2 must be smaller, that is, lens **210** must have a negative curvature. Conversely, if the voltage U_1 becomes smaller (resulting in a negative curvature for lens **205**), the voltage U_2 must be larger (resulting in a positive curvature for lens **210**). That is, the voltages applied to lenses **205-210** are applied to have one lens change its curvature in one direction and the other lens change its curvature in the opposite direction. The effect of the applicable voltages on the curvature of the lenses can be described as follows.

[0051] With various optical distances between double-liquid variable focal lenses **205-210** as illustrated, the distance l" between image point P' (marking the location of the image plane) and double-liquid variable focal lens **210** can be expressed as:

$$l'' = \frac{n_0}{n_2}\left(\frac{n_2 R'_5\left(\frac{n_1}{n_0}\left(\frac{n_0}{n_2}\left(\frac{n_2 R'_2}{n_2 - n_1} - d'_3\right) - d_4\right) - d'_5\right)}{\begin{array}{c} n_1 R'_5 + (n_2 - n_1) \\ \left(\frac{n_1}{n_0}\left(\frac{n_0}{n_2}\left(\frac{n_2 R'_2}{n_2 - n_1} - d'_3\right) - d_4\right) - d'_5\right) \end{array}} - (d_{02} - d'_5)\right) \tag{4}$$

$$\text{Now let } \beta = \frac{n_0}{n_2}\left(\frac{n_2 R'_2}{n_2 - n_1} - d'_3\right) - d_4 \tag{5}$$

Then

$$l'' = \frac{n_0}{n_2}\left(\frac{n_2 R'_5\left(\frac{n_1}{n_0}\beta - d'_5\right)}{n_1 R'_5 + (n_2 - n_1)\left(\frac{n_1}{n_0}\beta - d'_5\right)} - (d_{02} - d'_5)\right) \tag{6}$$

[0052] To make the image plane invariable, i.e., to make image point P" and distance l" fixed, let:

$$l'' = l' \tag{7}$$

This results in:

$$R'_5 = \frac{\left(l' + \frac{n_0}{n_2}(d_{02} - d'_5)\right)\left(\frac{n_1}{n_0}\beta - d'_5\right)(n_2 - n_1)}{n_0\left(\frac{n_1}{n_0}\beta - d'_5\right) - n_1\left(l' + \frac{n_0}{n_2}(d_{02} - d'_5)\right)} \tag{8}$$

Applying geometric relations between the various optical distances illustrated results in:

$$d'_2 = k_1 d_{01} + (2R'^3_2 + 2R'^2_2(R'^2_2 - a_1^2)^{1/2} - 3a_1^2 R'_2 - 2a_1^2 (R'^2_2 - a_1^2)^{1/2})/(3a_1^2),\ R'_2 < 0 \tag{9}$$

$$d'_5 = k_2 d_{02} + (2R'^3_5 - 2R'^2_5(R'^2_5 - a_2^2)^{1/2} - 3a_2^2 R'_5 + 2a_2^2 (R'^2_5 - a_2^2)^{1/2})/(3a_2^2),\ R'_5 > 0 \tag{10}$$

where a_1 and a_2 are the radius of lenses **205-210**, respectively, and k_1 and k_2 are the volume percentages of insulating liquids **220-230** relative to the total liquid in lenses **205-210**, respectively.

[0053] As described above, the voltages U_1 and U_2 applied to lenses **205-210**, respectively, are related to the radii of liquid interfaces **305-310** in lenses **205-210** as follows:

$$R'_2 = -a_1/(\cos\theta_0 + \epsilon_0\epsilon_r U_1^2/(2\gamma_{12} d)) \tag{11}$$

$$R'_5 = -a_2/(\cos\theta_0 + \epsilon_0\epsilon_r U_2^2/(2\gamma_{12} d)) \tag{12}$$

where θ_0 is the initial contact angle when the applied voltages are zero, γ_{12} is the interfacial tension between the conducting and insulating liquids in each lens, and d is the thickness of the dielectric layer (not shown) coated inside the cylindrical chamber of lenses **205-210**.

[0054] On the basis of Gaussian optical theory, the focal length of optical imaging apparatus can, therefore, be expressed as:

$$f = \frac{n_0 n_1 R'_2 R'_5}{(n_2 - n_1)\left(\frac{n_1 R'_5 + (n_2 - n_1)}{\left(\frac{n_1}{n_0}\left(\frac{n_0}{n_2}\left(\frac{n_2 R'_2}{n_2 - n_1} - d'_3\right) - d'_4\right) - d'_5\right)}\right)} \tag{13}$$

[0055] The relationship between the voltage U_1 applied to lens **205** and the focal length f of optical imaging apparatus **300** is illustrated in FIG. **4**. Graph **400** shows an almost linear relationship between the applied voltage U_1 to lens **205** and the focal length f of optical imaging apparatus **300**. That is, the focal length f can be varied by simply changing the applied voltages U_1 and U_2, while the image plane (represented by the image point P' and the distance l" in Equation (5) above) is kept invariable.

[0056] Referring now to FIG. **5**, a flow chart for providing a plurality of focal lengths without mechanical movements in accordance with an embodiment of the invention is described. A first and a second double-liquid variable focal lenses are designed to be operable with opposite varying curvatures (**500**). The first and second double-liquid variable focal lenses may be, for example, lenses **205-210** described above.

[0057] In one embodiment, the first double-liquid variable focal lens may be designed to be a concave lens and the second double-liquid variable focal lens may be designed to be a convex lens. Alternatively, in another embodiment, the first double-liquid variable focal lens may be designed to be a convex lens and the second double-liquid variable focal lens may be designed to be a concave lens.

[0058] The first and second double-liquid variable lenses are then aligned on a common axis (**505**). Voltages may be applied to the first and/or second double-liquid variable lenses as described above with reference to FIGS. **2-3**, in order to change the curvature of the lenses and provide a plurality of variable focal lengths. By varying the lenses' curvatures in opposite directions and by using conducting and insulating liquids that have substantially the same density but different refractive indices, the image plane of the optical imaging apparatus remains fixed while the focal length changes.

[0059] Referring now to FIG. **6**, a flow chart for fabricating an optical imaging apparatus having a variable focal length in accordance with an embodiment of the invention is described. First, a first and a second double-liquid variable focal lenses are fabricated (**600**). The first and the second double-liquid variable focal lenses may be designed as described above with references to lenses **205-210**.

[0060] Next, the first and the second double-liquid variable focal lenses are arranged in a package and aligned on a common axis (**605**). Lastly, a programmable controller is provided in the package to supply voltages to the first and second double-liquid variable focal lenses (**610**). The voltages are used to change the curvature of the liquid interfaces in the double-liquid variable focal lenses, thereby changing the focal length of the optical imaging apparatus while keeping the image plane invariable.

[0061] In one embodiment, the controller may be programmable by a user. For example, the optical imaging apparatus may be a lens assembly in a camera device having a focus control input accessible by the user to change the focal length of the lens as desired. In this case, the programmable controller receives the input from the user and applies the appropriate voltages to the first and second double-liquid variable focal lenses in order to achieve the desired focal length.

[0062] Referring now to FIG. **7**, multiple configurations for the double-liquid variable focal lenses used in the optical imaging apparatuses of FIGS. **2-3** in accordance with an embodiment of the invention are described. Double-liquid variable focal lenses **205-210** each have a conducting and an insulating liquid. As described above, lenses **205-210** may have the same or a different conducting and insulating liquid. For example, lenses **205-210** may have the same conducting liquid and the same insulating liquid. The conducting liquid may be, for example, salted water with a refractive index of $n_1=1.38$, and the insulating liquid may be, for example, an oil liquid with a refractive index of $n_2=1.55$.

[0063] According to an embodiment of the invention, lenses **205-210** may have their conducting and insulating liquids placed in multiple configurations. For example, lens **205** in configuration **700** may have its insulating liquid facing the conducting liquid in lens **210** in configuration **705**, lens **205** in configuration **710** may have its conducting liquid facing the insulating liquid in lens **210** in configuration **715**, lens **205** in configuration **720** may have its insulating liquid facing the insulating liquid in lens **210** in configuration **725**, and lens **205** in configuration **730** may have its conducting liquid facing the conducting liquid in lens **210** in configuration **735**. It is appreciated that configurations **700-705**, **710-715**, **720-725**, and **730-735** are along a common axis, passing through the center of lenses **205-210**.

[0064] It is appreciated that configurations **720-725** and **730-735** are characterized by having the same type of liquid in lenses **205-210** facing each other. Accordingly, in one embodiment of the invention, a single, triple-layer double-liquid lens may be used to provide a variable focal length and an invariable image plane. The single, triple-layer, double-liquid lens is also formed of a cylindrical chamber and contains two liquids, one insulating and one conducting. However, in this embodiment, the two liquids are placed in three layers in a single, triple-layer, double-liquid lens, with one layer containing one type of liquid placed in between two layers containing the other type.

[0065] For example, the single, triple-layer, double-liquid lens could have an insulating liquid layer in between two conducting layers. Conversely, the single, triple-layer, double-liquid lens could have a conducting liquid layer in between two insulating layers. The first case would be similar to merging configurations **720-725** in a single lens, while the latter would be similar to merging configurations **730-735** in a single lens.

[0066] Referring now to FIG. **8**, an optical imaging apparatus having a single, triple-layer, double-liquid variable focal lens constructed in accordance with an embodiment of the invention is described. Optical imaging apparatus **800** has a single, triple-layer double-liquid variable focal lens **805** formed of a cylindrical chamber enclosing three liquid layers, with one liquid layer in between two liquid layers holding the same liquid. For example, triple-layer double-liquid variable focal lens **805** has an insulating liquid layer **820** in between two conducting liquid layers **810-815**.

[0067] Insulating liquid layer **820** is formed of an insulating liquid of refractive index n_1, and conducting liquid layers **810-815** are formed of a conducting liquid of refractive index n_2, with $n_1>n_2$. Similar to double-liquid variable focal lenses **205-210** described above with reference to FIGS. **2-3**, lens **805** also has an electrode layer **835** and an dielectric layer **840** coated inside the cylindrical chamber. And similar to double-liquid variable focal lenses **205-210**, lens **805** also provides a variable focal length while keeping the image plane invariable.

[0068] The three liquid layers form two liquid interfaces **825-830**. Liquid interface **825** is shown with a positive curvature while liquid interface **830** is shown with a planar curvature. Similar to double-liquid variable focal lenses **205-210** described above with reference to FIGS. **2-3**, the curvatures of liquid interfaces **825-830** can be controlled by changing the voltages applied between electrode layer **835** and conducting liquid layers **810-815**. As described below, an invariable image plane requires that liquid interfaces **825-830** have opposite varying curvatures.

[0069] With various optical distances as illustrated, the distance l' between image point P (marking the location of the image plane) and triple-layer, double-liquid variable focal lens **805** can be expressed as:

$$l' = \frac{n_0}{n_2}\left(\frac{n_2}{n_1}\left(\frac{n_2R_2}{n_2-n_1} - d_3\right) - d_4\right) \tag{14}$$

where the radius R_2 of liquid interface **825** is determined by the voltage U_1 applied between electrode layer **835** and conducting liquid layer **810**. Radius R_2 is related to the contact angle Θ and the radius a of the cylindrical chamber in lens **805** as follows:

$$R_2 = \frac{a}{\cos\theta} \tag{15}$$

[0070] That is, the focal length of optical imaging apparatus **800** depends mainly on the value of U_1 in this case. The voltage applied between electrode layer **835** and conducting liquid layer **815**, referred to as U_2, does not affect the focal length of optical imaging apparatus **800**. This is because voltage U_2 results in a planar curvature for liquid interface **830**. Changing the value of U_2 may result in a positive or negative curvature for liquid interface **830**. As described below, an invariable image plane requires liquid interfaces **825-830** to have opposite varying curvatures.

[0071] Referring now to FIG. **9**, an optical imaging apparatus having a single, triple-layer, double-liquid variable focal lens constructed in accordance with an embodiment of the invention is described. Optical imaging apparatus **900**

includes triple-layer, double-liquid variable focal lens **805**. Triple-layer, double-liquid variable focal lenses **805** has a liquid interface **905** with a positive curvature resulting from a voltage U_1 applied between electrode layer **835** and conducting liquid layer **810**, and a liquid interface **910** with a negative curvature resulting from a voltage U_2 applied between electrode layer **835** and conducting liquid layer **815**.

[0072] The opposite varying curvatures of interfaces **905-910** ensure that the image plane remains invariable while the focal length of optical imaging apparatus **900** changes. This is so because when the voltage U_1 makes the radius of the first liquid interface **905** smaller, the voltage U_2 must make the radius of the second liquid interface **910** larger to keep the image point (and the image plane) fixed. The effect of the applicable voltages on the curvatures of liquid interfaces **825-830** can be described as follows.

[0073] With various optical distances as illustrated, the distance l" between image point P' (marking the location of the image plane) and triple-layer, double-liquid variable focal lens **805** can be expressed as:

$$l'' = \frac{n_0}{n_2}\left(\frac{n_2 R_5'\left(\frac{n_1 R_2'}{n_1 - n_2} - d_3'\right)}{n_1 R_5' + (n_2 - n_1)\left(\frac{n_1 R_2'}{n_1 - n_2} - d_3'\right)} - d_4'\right) \tag{16}$$

Now let:

$$\beta = \frac{n_1 R_2'}{n_1 - n_2} - d_3' \tag{17}$$

$$l'' = \frac{n_0}{n_2}\left(\frac{n_2 R_5' \beta}{n_1 R_5' + (n_2 - n_1)\beta} - d_4'\right); \tag{18}$$

[0074] To make the image plane invariable, i.e., to make image point P" and distance l" fixed, let:

$$l''=l' \tag{19}$$

This results in:

$$R_5' = \frac{\left(l' + \frac{n_0}{n_2}d_4'\right)\beta(n_2 - n_1)}{n_0\beta - n_1\left(l' + \frac{n_0}{n_2}d_4'\right)} \tag{20}$$

[0075] Applying geometric relations between the various optical distances illustrated results in:

$$d'_2=d_0/3+(2R'^3_2+2R'^2_2(R'^2_2-a^2)^{1/2}-3a^2R'_2-2a^2(R'^2_2-a^2)^{1/2})/(3a^2),\ R'_2<0 \tag{21}$$

$$d'_2=d_0/3+(2R'^3_2-2R'^2_2(R'^2_2-a^2)^{1/2}-3a^2R'_2+2a^2(R'^2_2-a^2)^{1/2})/(3a^2),\ R'_2>0 \tag{22}$$

$$d'_5=d_0/3+(-2R'^3_5-2R'^2_5(R'^2_5-a^2)^{1/2}+3a^2R'_5+2a^2(R'^2_5-a^2)^{1/2})/(3a^2),\ R'_5<0 \tag{22}$$

$$d'_5=d_0/3+(-2R'^3_5+2R'^2_5(R'^2_5-a^2)^{1/2}+3a^2R'_5-2a^2(R'^2_5-a^2)^{1/2})/(3a^2),\ R'_5>0 \tag{22}$$

where a is the radius of the cylindrical chamber in lens **825** and each liquid layer covers ⅓ of the total liquid volume in the chamber.

[0076] The voltages U_1 and U_2 are related to the radii of liquid interfaces **905-910** in lens **85** as follows:

$$R'_2=-a/(\cos\theta_0+\epsilon_0\epsilon_r U_1^2/(2\gamma_{12}d)) \tag{25}$$

$$R'_5=-a/(\cos\theta_0+\epsilon_0\epsilon_r U_2^2/(2\gamma_{12}d)) \tag{26}$$

where Θ_0 is the initial contact angle when the applied voltages are zero, γ_{12} is the interfacial tension between the conducting and insulating liquids, and d is the thickness of dielectric layer **840**.

[0077] On the basis of Gaussian optical theory, the focal length of optical imaging apparatus **900** can, therefore be expressed as:

$$f = \frac{n_0 n_1 R_2' R_5'}{(n_1 - n_2)\left(n_1 R_5' + (n_2 - n_1)\left(\frac{n_1 R_2'}{n_1 - n_2} - d_3'\right)\right)} \tag{27}$$

[0078] The relationship between the voltage U_1 and the focal length f of optical imaging apparatus **900** is illustrated in FIG. **10**. Graph **1000** shows an almost linear relationship between the applied voltage U_1 and the focal length f of optical imaging apparatus **900**. That is, the focal length f can be varied by simply changing the applied voltages U_1 and U_2, while the image plane (represented by the image point P' and the distance l" in Equation (17) above) is kept invariable.

[0079] It is appreciated by one of ordinary skill in the art that lens **805** is shown with two conducting layers **810-815** and one insulating layer **820** for illustration purposes only. A lens having two insulating layers and one conducting layer may also be used to provide a variable focal length and an invariable image plane.

[0080] According to another embodiment of the invention, an optional fixed lens may be combined with the double-liquid lenses described above (i.e., lens **205-210** and lens **805**). The fixed lens may be used to improve the optical properties of the optical imaging apparatus while keeping the image plane invariable for a variable focal length. Those optical properties may include, for example, dispersion, zoom capabilities, and chromatic aberration, among others.

[0081] Referring now to FIG. **11**, an optical imaging apparatus constructed in accordance with an embodiment of the invention is described. Optical imaging apparatus **1100** includes fixed lens **1105**, double-liquid variable focal lens **1110**, and double-liquid variable focal lens **1115**. In this embodiment, double-liquid variable focal lenses **1110-1115** are placed between the exit pupil and the back focus plane of fixed lens **1105**. Fixed lens **1105** and double-liquid variable focal lenses **1110-1115** are all aligned on a common axis **1120**, passing through the center of lenses **1105-1115**.

[0082] Double-liquid variable focal lenses **1110-1115** may be any double-liquid variable focal lens known to one of ordinary skill in the art, such as, for example, double-liquid variable focal lens **205-210** shown in FIGS. **2-3**. According to an embodiment of the invention, lenses **1110-1115** are designed to have opposite varying curvatures. For example, lens **1110** may be a concave (i.e., negative) lens and lens **1115** may be a convex (i.e., positive) lens as shown. Alternatively, lens **1110** may be a convex lens and lens **1115** may be a concave lens. As described in more detail herein below, the opposite varying curvatures of the lenses enables the focal or image plane of optical imaging apparatus **1100** to remain invariable for a variable focal length.

[0083] It is appreciated by one of ordinary skill in the art that the focal power of optical imaging apparatus **1100** is mainly determined by fixed lens **1105**. It is also appreciated that the curvature of lenses **1110-1115** may be modified as desired by the voltages applied to lenses **1110-1115** (while still keeping the curvatures to have opposite signs). That is, the voltages applied to lenses **1110-1115** are applied to have one lens change its curvature in one direction and the other lens change its curvature in the opposite direction. For example, when lens **1110** acts as a concave lens and lens **1115** acts as a convex lens under applied voltages, lens **1110** diverges incoming light rays and lens **1115** converges the rays. That is, the convergence angle on the image plane of fixed lens **1105** increases and the combined focal length of optical imaging apparatus **1100** decreases if the image plane remains fixed. Conversely, the combined focal length of optical imaging apparatus **1100** increases when lens **1110** acts as a convex lens and lens **1115** acts as a concave lens under applied voltages.

[0084] It is further appreciated that the focal length of optical imaging apparatus **1100** can be readily adjusted by changing the applied voltages without any mechanical movements. In addition, a proper regulation of the applied voltages can also ensure that the summation of conjugate distances of lenses **1105-1115** remains fixed, farther contributing to an invariable image plane.

[0085] An invariable image plane results in better focus of the image in the image acquisition surface, such as a camera film or image sensor, thereby leading to improved image quality. The lack of mechanical movements to achieve a variable focal length while keeping the image plane invariable makes the optical imaging apparatus of the invention especially suitable for use in small cameras (such as those in mobile devices) or any other device where robustness, size, speed, power consumption, and ease of use are of crucial importance.

[0086] FIG. **12** illustrates an optical imaging apparatus constructed in accordance with another embodiment of the invention. Optical imaging apparatus **1200** has double-liquid variable focal lens **1110**, double-liquid variable focal lens **1115**, and fixed lens **1105** arranged in a different configuration. In this embodiment, double-liquid variable focal lenses **1110-1115** are placed before fixed lens **1105**. It is appreciated that the image plane of optical imaging apparatus **1200** is kept invariable, while its image plane changes.

[0087] Referring now to FIG. **13**, a schematic diagram of an optical imaging apparatus when both double-liquid variable focal lenses operate with planar liquid interfaces in accordance with an embodiment of the invention is described. Optical imaging apparatus **1300** includes fixed lens **1305**, double-liquid variable focal lens **1310** and double-liquid variable focal lens **1315**, aligned along common axis **1320**, passing through the center of lenses **1305-1315**.

[0088] In the embodiment shown, double-liquid variable focal lenses **1310-1315** have a liquid **1** and a liquid **2**. Liquid **1** may be a conducting or insulating liquid. Conversely, liquid **2** may be an insulating (when liquid **1** is a conducting liquid) or conducting (when liquid **1** is an insulating liquid) liquid. For illustration and description purposes, liquid interface **1325** in double-liquid variable focal lens **1310** and liquid interface **1330** in double-liquid variable focal lens **1315** are a plane under applicable voltages.

[0089] In this case, when liquid interfaces **1325-1330** become a plane under applicable voltages, double-liquid variable focal lenses **1310-1315** can be treated as a plane-parallel plate, which has no contribution to the total focal power of optical imaging apparatus **1300**. That is, two double-liquid variable focal lenses can only change the focus position of the optical imaging apparatus **1300**, i.e., they can only change the focal length of the optical imaging apparatus **1300**. The focal power of the optical imaging apparatus **1300** is determined by fixed lens **1305**.

[0090] The focus position of the optical imaging apparatus, defined by l', i.e., the distance from the focus point P to the back surface of the second double-liquid variable focal lens **1315**, can be expressed as:

$$l'=(f_0-d_1)-n_0d_2/n_1-n_0d_3/n_2-d_4-n_0d_5/n_1-n_0d_5/n_2 \tag{28}$$

where n_0 is the refractive index of air, n_1 is the refractive index of liquid **1** as illustrated, n_2 is the refractive index of liquid **2** as illustrated, f_0 is the focal length of fixed lens **1305**, and d_1, d_2, d_3, d_4, d_5, and d_6 are distances as illustrated.

[0091] For a optical imaging apparatus **1300**, l' is a constant, that is, the image plane is fixed. Now let the thickness of the first and second double-liquid variable focal lenses **1310-1315** be expressed by d_{01} and d_{02}, respectively, the volume percentage of liquid **2** in lens **1310** be expressed by k_1 and the volume percentage of liquid **2** in lens **1315** be expressed by k_2. That is, $d_2=k_1d_{01}$ and $d_5=k_2d_{02}$. Equation (28) above may then be rewritten as:

$$l'=(f_0-d_1-d4)-n_0(k_1d_{01}+k_2d_{02})(n_2-n_1)/(n_1n_2)=n_0(d_{01}+d_{02})/n_2 \tag{29}$$

[0092] In the general case, liquid interfaces **1325-1330** may be either convex or concave. To keep the focus position of the optical imaging apparatus **1300** invariable, one of the liquid interfaces **1325-1330** is a convex interface while the other is a concave interface. That is, the curvatures of interfaces **1325-1330**, i.e., the curvature of lenses **1310-1315**, are opposite curvatures.

[0093] Referring now to FIG. **14**, a schematic diagram of an optical imaging apparatus with non-zero focal power for both double-liquid variable focal lenses in accordance with an embodiment of the invention is described. Optical imaging apparatus **1400** has fixed lens **1405**, double-liquid variable focal lens **1410** and double-liquid variable focal lens **1415**, all aligned along common axis **1420**, passing through the center of lenses **1405-1415**.

[0094] In this embodiment, double-liquid variable focal lens **1410** has a concave interface (i.e., negative radii r_2) while double-liquid variable focal lens **1415** has a convex interface (i.e., positive radii r_5). The focus position l" of optical imaging apparatus **1400** in this case can be expressed as:

$$l' = \frac{n_0}{n_2}\cdot\left[\frac{n_2(n_1\alpha/n_0-d_5')r_5}{n_1r_5+(n_1\alpha/n_0-d_5')(n_2-n_1)}-(d_{02}-d_5')\right] \tag{30}$$

where

$$\alpha = \frac{n_0}{n_2}\left\{\begin{array}{c}\dfrac{n_2r_2[n_1(f_0-d_1)/n_0-d_2']}{n_1r_2+[n_1(f_0-d_1)/n_0-d_2'](n_2-n_1)}- \\ (d_{01}-d_2')\end{array}\right\}-d_4 \tag{31}$$

[0095] Since r_2 (or r_5) and d'_2 (or d'_5) are geometrically related, the latter can be expressed as a function of the former, that is:

$$d'_2=k_1d_{01}[2r_2^3+2r_2^2(r_2^2-a_1^2)^{1/2}-3a_1^2r_2-2a_1^2(r_2^2-a_1^2)^{1/2}]/(3a_1^2),\ r_2<0 \tag{32}$$

$$d'_5=k_2d_{02}[2r_5^3-2r_5^2(r_5^2-a_2^2)^{1/2}-3a_2^2r_5+2a_2^2(r_5^2-a_2^2)^{1/2}]/(3a_2^2),\ r_5>0 \tag{33}$$

where a_1 and a_2 are the inner radius of the cylindrical chambers in double-liquid variable focal lenses **1410-1415**, respectively.

[0096] Equations (32) and (33) above also show that the absolute value for both r_2 and r_5 have a lower limit, that is, $|r_2| \geqq a_1$ and $|r_5| \geqq a_2$. To keep the focus position, i.e., the image plane of optical imaging apparatus **800** fixed, the following holds:

$$l'' = l' \tag{34}$$

[0097] Substituting Equation (30) into Equation (34), results in:

$$r_5 = \frac{(n_2 l' + d_{02} - d_5')(n_1\alpha - d_5')(n_2 - n_1)}{n_2(n_1\alpha - d_5') - n_1(n_2 l' + d_{02} - d_5')} \tag{35}$$

where α is a unction of r_2 and r_5 is implicated in d'_5. When r_2, which is determined by the voltage applied to lens **1410**, is given, Equation (35) can be solved analytically. However, this results in a higher-order equation in terms of r_5 having extraneous roots. The relation between r_5 and r_2 can be achieved by a numerically iterative method.

[0098] Let the voltages applied to lenses **1410-1415** be U_1 and U_2, respectively. According to Equation (1), the following holds:

$$r_2 = -a_1/[\cos\theta_0 + \epsilon_0\epsilon_r U_1^2/(2\gamma_{12} d)] \tag{36}$$

$$r_5 = -a_2/[\cos\theta_0 + \epsilon_0\epsilon_r U_2^2/(2\gamma_{12} d)] \tag{37}$$

[0099] Since there exits a one-to-one correspondence between the applied voltages U_1 and U_2 and the liquid interface radii r_2 and r_5, the relationship between r_2 and r_5 can be readily expressed into that of U_1 and U_2. Under such circumstances, the combined focal length of optical imaging apparatus **800**, denoted by f, can be expressed in r_2 and r_5 as:

$$f = \frac{n_1^2 r_2 r_5 f_0}{\left\{\frac{n_1 r_2 + [n_1(f_0 - d_1)/n_0 - d_2']}{(n_2 - n_1)}\right\} - [n_2 - n_1)(n_1\alpha/n_0 - d_5') + n_1 r_5]} \tag{38}$$

[0100] It is appreciated that Equation (38) above indicates that the focal length of optical imaging apparatus **1400** varies only with the radii r_2 and r_5 of lenses **1410-1415**, which, in turn, vary with the applied voltages U_1 and U_2, respectively. That is, changing the voltage applied to lenses **1410-1415** results in a variable focal length for the entire optical imaging apparatus **1400** while the image plane is kept invariable (with the lenses **1410-1415** having opposite varying curvatures).

[0101] In addition, it is appreciated that the contribution of fixed lens **1405** in Equation (38) above, i.e., the contribution of fixed lens **1405** to the focal length of optical imaging apparatus **1400** is mainly due to its focal length f_0 and to its positioning relative to double-liquid variable focal lenses **1410-1415**. It is then appreciated that fixed lens **805** is arranged relative to double-liquid variable focal lenses **1410-1415** in order to achieve an extended range of focal lengths f given the practical range of applicable voltages U_1 and U_2 (typically around 0-100 V).

[0102] It is further appreciated that a similar derivation can be performed for the case where lens **1410** is a convex lens and lens **1415** is a concave lens. Optical imaging apparatus **1400** can therefore realize the function of zooming and focusing to observe a large area with small magnification or a small area with large magnification.

[0103] In order to illustrate the focal properties of the optical imaging apparatus of the invention, simulation results are described below. A set of parameters are specified as follows: n_0-1, $n_1-1.38$, $n_2-1.55$, $d_{01}-d_{02}-2$ mm, $d_1=0.05$ mm, $d_4=2.95$ mm, $k_1=1/3$, $k_2=2/3$, and $f_0=10$ mm.

[0104] Referring now to FIG. **15**, a graph showing the interface radius of the second double-liquid variable focal lens as a function of the interface radius of the first double-liquid variable focal lens in accordance with an embodiment of the invention is described. Graph **1500** shows radius r_5 of lens **1415** as a function of radius r_2 of lens **1410** according to Equation (35) above. As shown in FIG. **15**, the signs of r_5 and r_2 remain opposite. Due to the limits mentioned earlier for r_2 and r_5, there exists a gap **1505** in graph **1500** corresponding to the limited range.

[0105] Additional simulation results can be obtained by specifying the inner radii (for example $a_1=a_2=1$ mm) and choose two liquids with a liquid interface tension coefficient of $\gamma_{12}=38.1\times10^{-3}$ N/m for two double-liquid variable focal lenses. Referring now to FIG. **16**, a graph showing the voltage applied to the second double-liquid variable focal lens as a function of the voltage applied to the first double-liquid variable focal lens in accordance with an embodiment of the invention is described. The relationship between voltages U_2 and U_1 can be simulated for different dielectric thicknesses. Graph **1600** shows the resulting relationship between U_2 and U_1.

[0106] Referring now to FIG. **17**, a graph showing the focal length of an optical imaging apparatus constructed in accordance with an embodiment of the invention as a function of the voltage applied to the first double-liquid variable focal lens is described. Graph **1700** shows the focal length of optical imaging apparatus **1400** as a function of the applied voltage U_1 for two different thicknesses of the dielectric layer.

[0107] As shown in FIG. **17**, for a dielectric layer with larger thickness (curve **1705**), larger voltages are required in order to obtain the same range of the focal length for optical imaging apparatus **1400**. In one embodiment, the continuous optical zoom of optical imaging apparatus **1400** can reach up to 1:2 while keeping the image plane invariable.

[0108] It is appreciated that the simulation results shown in FIGS. **15-17** do not consider any aberrations. It is also appreciated that Equations (28)-(38) above are based on an infinite object and that similar derivations can be made for finite objects.

[0109] Referring now to FIG. **18**, a programmable multi-focal camera constructed in accordance with an embodiment of the invention is described. Programmable multi-focal camera **1800** includes an image sensor **1805** and an optical imaging apparatus having an optional fixed lens **1810**, a first and a second double-liquid variable focal lenses **1815-1820**, and a programmable controller **1825**. As described above, programmable controller **1825** provides voltages to lenses **1815-1820** to result in a plurality of focal lengths while keeping the image plane invariable. The focal lengths can be specified by a user as desired, via focal selection input **1830**.

[0110] FIG. **19** illustrates a programmable multi-focal camera constructed in accordance with another embodiment of the invention. Programmable multi-focal camera **1900** includes an image sensor **1905** and an optical imaging apparatus having a triple-layer, double-liquid variable focal lens **1910**, and a programmable controller **1925**. As described above, programmable controller **1925** provides voltages to lens **1910** to result in a plurality of focal lengths while keeping the image plane invariable. The focal lengths can be specified by a user as desired, via focal selection input **1930**.

[0111] Advantageously, the optical imaging apparatuses of the invention provide multiple focal lengths in a single, small and efficient package that can be programmed and electrically controlled to provide fast focal speed and accuracy. The package may be used in a variety of imaging devices, including, but not limited to, viewing devices such as glasses, binoculars and telescopes, scientific instruments such as microscopes and spectroscopes, analog and digital cameras, video cameras, medical devices such as optical catheter and endoscopes, and the like.

[0112] For example, an optical imaging apparatus may be integrated into a programmable camera for achieving multiple selectable focal lengths while keeping the image plane invariable. An invariable image plane results in better focus of the image in the image sensor, thereby leading to improved image quality. The lack of mechanical movements to achieve a variable focal length while keeping the image plane invariable makes the optical imaging apparatuses of the invention especially suitable for use in small cameras (such as those in mobile devices) or any other device where robustness, size, speed, power consumption, and ease of use are of crucial importance.

[0113] The programmable camera allows users to seamlessly and speedily change focal lengths while capturing images at varying distances. In contrast with traditional zoom lenses, the optical imaging apparatuses built according to embodiments of the invention are fast, provide a more accurate focus, has lower power consumption, fewer optical elements and is easily miniaturized.

[0114] The foregoing description, for purposes of explanation, used specific nomenclature to provide a thorough understanding of the invention. However, it will be apparent to one skilled in the art that specific details are not required in order to practice the invention. Thus, the foregoing descriptions of specific embodiments of the invention are presented for purposes of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed; obviously, many modifications and variations are possible in view of the above teachings. The embodiments were chosen and described in order to best explain the principles of the invention and its practical applications; they thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated. It is intended that the following claims and their equivalents define the scope of the invention.

1. An optical imaging apparatus having a variable focal length, comprising:

a first double-liquid variable focal lens; and

a second double-liquid variable focal lens,

the first and second double-liquid variable focal lenses aligned on a common axis and operable to have opposite varying curvatures.

2. The optical imaging apparatus of claim **1**, further comprising a fixed lens aligned with the first and second double-liquid variable focal lenses.

3. The optical imaging apparatus of claim **1**, further comprising a programmable controller configured to independently address a first voltage to the first double-liquid variable focal lens and a second voltage to the second double-liquid variable focal lens to provide a plurality of focal lengths and an invariable image plane.

4. The optical imaging apparatus of claim **3**, wherein the first voltage is applied to the first double-liquid variable lens to generate a first curvature.

5. The optical imaging apparatus of claim **4**, wherein the second voltage is applied to the second double-liquid variable lens to generate a second curvature.

6. The optical imaging apparatus of claim **5**, wherein the first curvature is a convex curvature and the second curvature is a concave curvature.

7. The optical imaging apparatus of claim **6**, wherein the first curvature is a concave curvature and the second curvature is a convex curvature.

8. The optical imaging apparatus of claim **1**, wherein the first double-liquid variable focal lens comprises:

a first cylindrical chamber enclosing a first liquid and a second liquid having substantially the same density and different refractive indices; and

an electrode layer and a hydrophobic dielectric layer coated inside the first cylindrical chamber.

9. The optical imaging apparatus of claim **8**, wherein the second double-liquid variable focal lens comprises:

a second cylindrical chamber enclosing a third liquid and a fourth liquid having substantially the same density and different refractive indices; and

an electrode layer and a hydrophobic dielectric layer coated inside the second cylindrical chamber.

10. The optical imaging apparatus of claim **9**, wherein the first liquid comprises a first conductive liquid and the second liquid comprises a first insulating liquid.

11. The optical imaging apparatus of claim **10**, wherein the third liquid comprises a second conductive liquid and the second liquid comprises a second insulating liquid.

12. A method for providing a plurality of focal lengths without mechanical movements, comprising:

designing a first and a second double-liquid variable focal lenses operable to have opposite varying curvatures; and

aligning the first and second double-liquid variable focal lenses on a common axis.

13. The method of claim **12**, further comprising providing a fixed lens aligned with the first and second double-liquid variable focal lenses on the common axis.

14. The method of claim **13**, further comprising:

applying a first voltage to the first double-liquid variable focal lens to control a first curvature; and

applying a second voltage to the second double-liquid variable focal lens to control a second curvature, the second curvature controlled to be opposite from that of the first curvature.

15. The method of claim **14**, further comprising varying the first and second voltages to provide a plurality of focal lengths.

16. A method of fabrication of an optical imaging apparatus having a variable focal length, comprising:

fabricating a first and a second double-liquid variable focal lenses;

arranging the first and the second double-liquid variable focal lenses in a package; and providing a programmable controller in the package to apply a first voltage to the first double-liquid variable focal lens and a second voltage to the second double-liquid variable focal lens,

the first voltage controlling a first curvature on the first double-liquid variable focal lens and the second voltage controlling a second curvature on the second double-liquid variable focal lens.

17. The method of claim **16**, further comprising providing a fixed lens in the package, the fixed lens aligned on a common axis with the first and second double-liquid variable focal lenses.

18. The method of claim **17**, further comprising varying the first and second voltages to keep the second curvature varying oppositely from the first curvature to provide an invariable image plane.

19. A programmable multi-focal camera, comprising:

an image sensor to generate image data from an optical image; and

a programmable optical assembly to capture the optical image, the programmable optical assembly comprising:

a first and a second double-liquid variable focal lens; and

a programmable controller configured to independently address a first voltage to the first double-liquid variable focal lens and a second voltage to the second double-liquid variable focal lens to provide a plurality of focal lengths and an invariable image plane at the image sensor.

20. The programmable multi-focal camera of claim **19**, wherein the programmable optical assembly further comprises a fixed lens aligned on a common axis with the first and second double-liquid variable focal lenses.

21. The programmable multi-focal camera of claim **20**, wherein the programmable controller comprises an input for selecting a focal length from the plurality of focal lengths.

22. The programmable multi-focal camera of claim **21**, wherein the first double-liquid variable focal lens comprises:

a first cylindrical chamber;

a first and a second liquid enclosed within the first cylindrical chamber,

the first and second liquids having substantially the same density and different refractive indices;

a first hydrophobic dielectric layer coated inside the first cylindrical chamber; and

a first electrode layer coated on the first hydrophobic dielectric layer.

23. The programmable multi-focal camera of claim **22**, wherein the second double-liquid variable focal lens comprises:

a second cylindrical chamber;

a third and a fourth liquid enclosed within the second cylindrical chamber,

the third and fourth liquids having substantially the same density and different refractive indices;

a second hydrophobic dielectric layer coated inside the second cylindrical chamber; and

a second electrode layer coated inside the second hydrophobic dielectric layer.

24. The programmable multi-focal camera of claim **23**, wherein the first and third liquid comprise a conductive liquid.

25. A variable focal lens, comprising:

a cylindrical chamber;

a first and a second liquid layers enclosed within the cylindrical chamber and holding a liquid of a first type; and

a third liquid layer in between the first and the second liquid layers and holding a liquid of a second type.

26. The variable focal lens of claim **25**, wherein the liquid of a first type comprises a conducting liquid and the liquid of a second type comprises an insulating liquid.

27. The variable focal lens of claim **26**, wherein the liquid of a first type comprises an insulating liquid and the liquid of a second type comprises a conducting liquid.

28. The variable focal lens of claim **27**, wherein the first liquid layer and the third liquid layer form a first liquid interface and the second liquid layer and the third liquid layer form a second liquid interface.

29. The variable focal lens of claim **28**, wherein the first and the second liquid interfaces have opposite varying curvatures.

30. The variable focal lens of claim **29**, wherein the conducting liquid and the insulating liquid have substantially the same density and different refractive indices.

31. The variable focal lens of claim **25**, further comprising:

a hydrophobic dielectric layer coated inside the cylindrical chamber; and

a electrode layer coated inside the hydrophobic dielectric layer.

32. A method of fabrication of an optical imaging apparatus having a variable focal length, comprising:

fabricating a triple-layer, double-liquid variable focal lens, having a first and a second liquid layers holding a liquid of a first type and a third liquid layer holding a liquid of a second type placed in between the first and the second liquid layers;

arranging the triple-layer, double-liquid variable focal lens in a package; and

providing a programmable controller in the package to apply voltages to the liquid layers.

33. The method of claim **32**, wherein the liquid of a first type comprises a conducting liquid and the liquid of a second type comprises an insulating liquid.

34. The method of claim **33**, wherein the liquid of a first type comprises an insulating liquid and the liquid of a second type comprises a conducting liquid.

35. The method of claim **34**, wherein the first liquid layer and the third liquid layer form a first liquid interface and the second liquid layer and the third liquid layer form a second liquid interface.

36. The method of claim **35**, wherein providing the programmable controller comprises applying a voltage to the first and the second liquid layers, the first and the second liquid layers holding a conducting liquid and the third liquid layer holding an insulating liquid.

37. The method of claim **35**, wherein providing the programmable controller comprises applying a voltage to the third liquid layer, the third liquid layer holding a conducting liquid and the first and the second liquid layers holding an insulating liquid.

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